

# Determination of the proton charge radius during the ULQ<sup>2</sup> experiment

Clement Legris, on behalf of the ULQ<sup>2</sup> collaboration

RARiS, Tohoku University

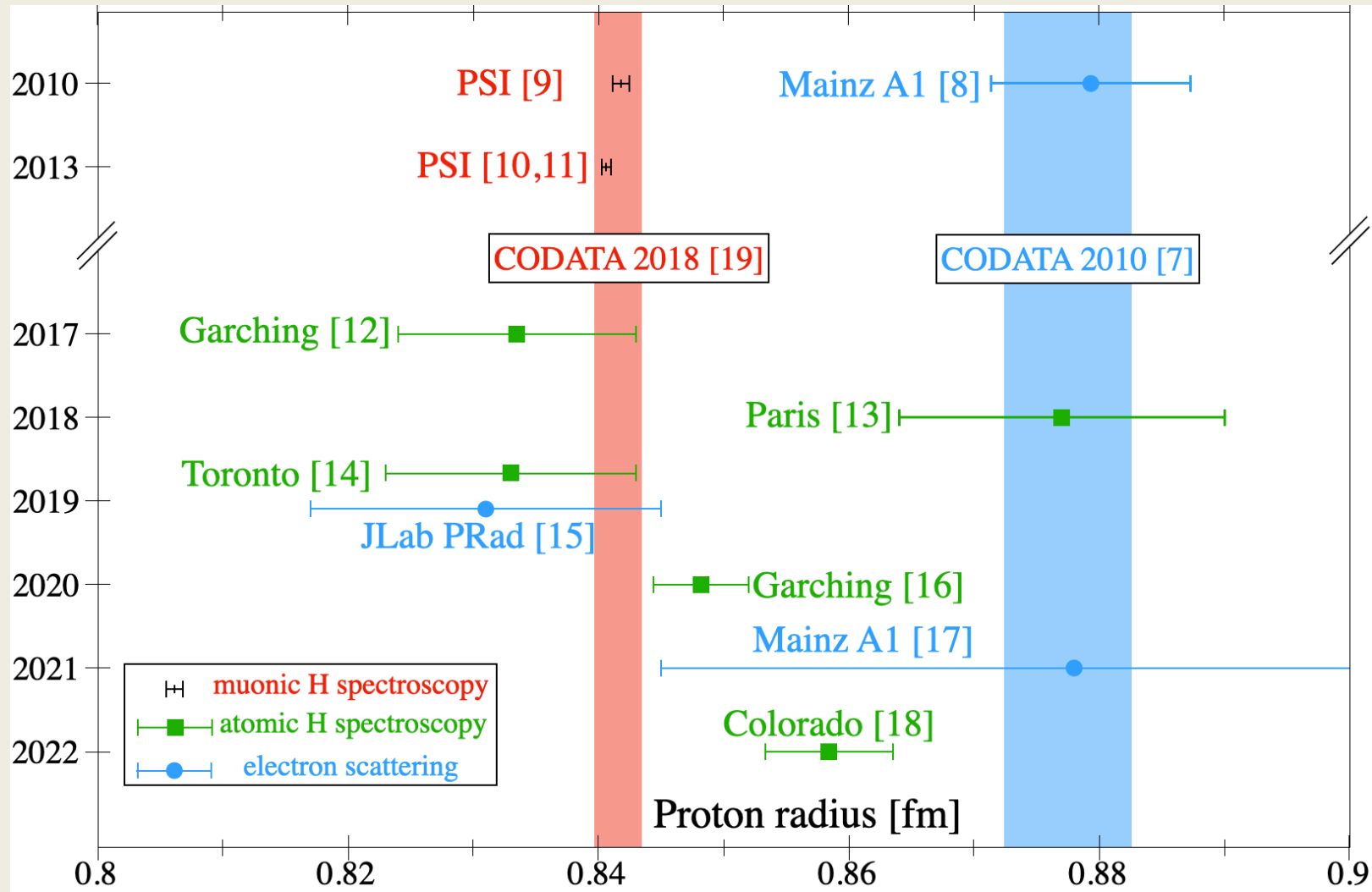
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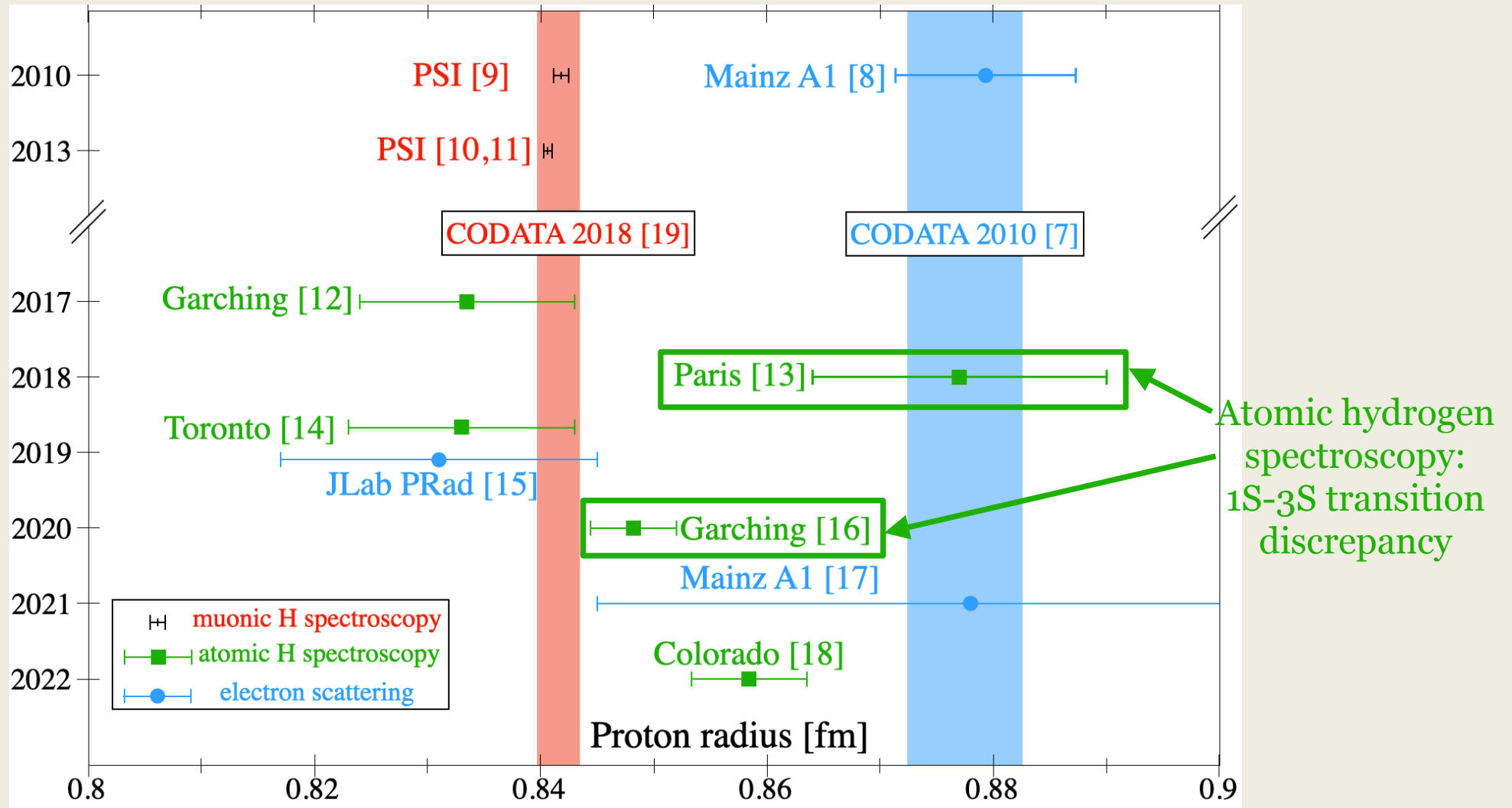


# I. Proton charge radius puzzle

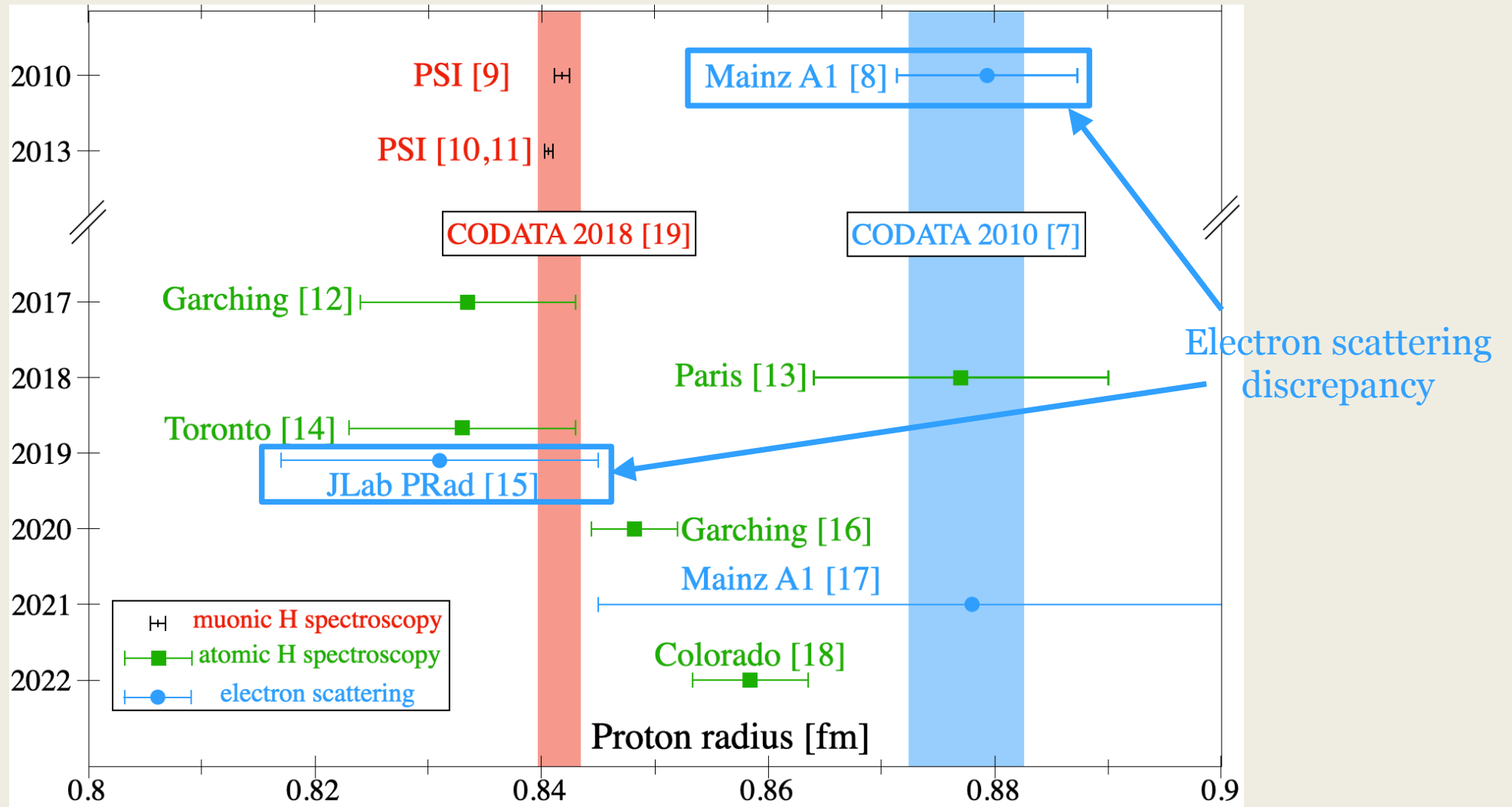
# Proton charge radius puzzle



# Proton charge radius puzzle



# Proton charge radius puzzle



## II. Determination of the proton charge radius with electron scattering

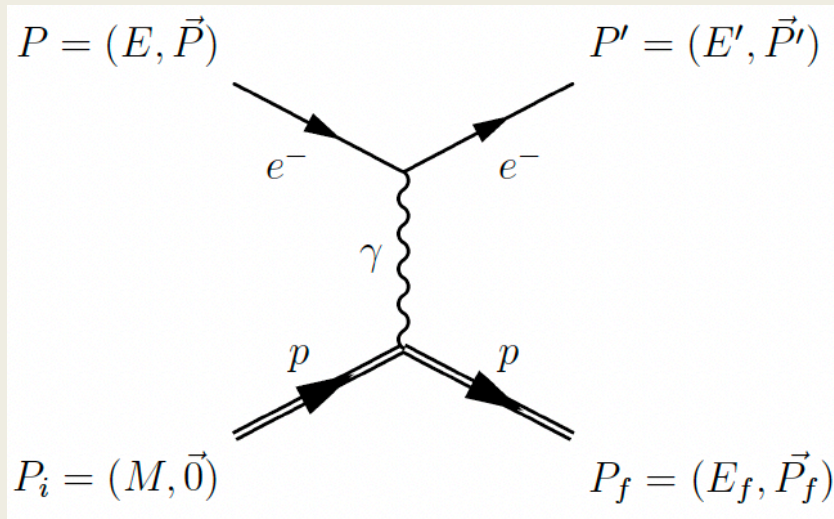
# Electric form factor and proton charge radius

$$\tau = \frac{Q^2}{4M_p^2}, \epsilon^{-1} = 1 + 2(1 + \tau) \frac{Q^2 - 2m^2}{4EE' - Q^2}$$

E. Borie, arXiv: 1207.6651v4

Momentum transfer:

$$Q^2 = -(P - P')^2$$



Feynman diagram of the leading-order of the electron-proton scattering.

Cross section:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \frac{G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)}{1 + \tau}$$

with  $\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{\alpha^2(4EE' - Q^2)}{Q^4} \frac{P'/P}{1 + (E - (PE'/P')\cos\theta)/M}$

$$R_E = \sqrt{\langle r_E^2 \rangle} \equiv \sqrt{-6 \lim_{Q^2 \rightarrow 0} \frac{dG_E}{dQ^2}}$$

G. Miller, Phys. Rev. C **99** (2019), 035202

**$Q^2$  as small as possible!**

# Specifications of the **ULQ<sup>2</sup>** experiment

## Ultra Low **Q<sup>2</sup>**

### Characteristics of the experiment:

- Measurement of  $G_E(Q^2)$  for extremely small values of  $Q^2$ :  
 $0.0003 \text{ (GeV/c)}^2 \leq Q^2 \leq 0.008 \text{ (GeV/c)}^2$
- **Lowest beam energy for electron scattering in the world:**  
 $10 \text{ MeV} \leq E \leq 60 \text{ MeV}$
- Polyethylene (CH<sub>2</sub>) target.  
    ➔ **Absolute** cross-section measurement.

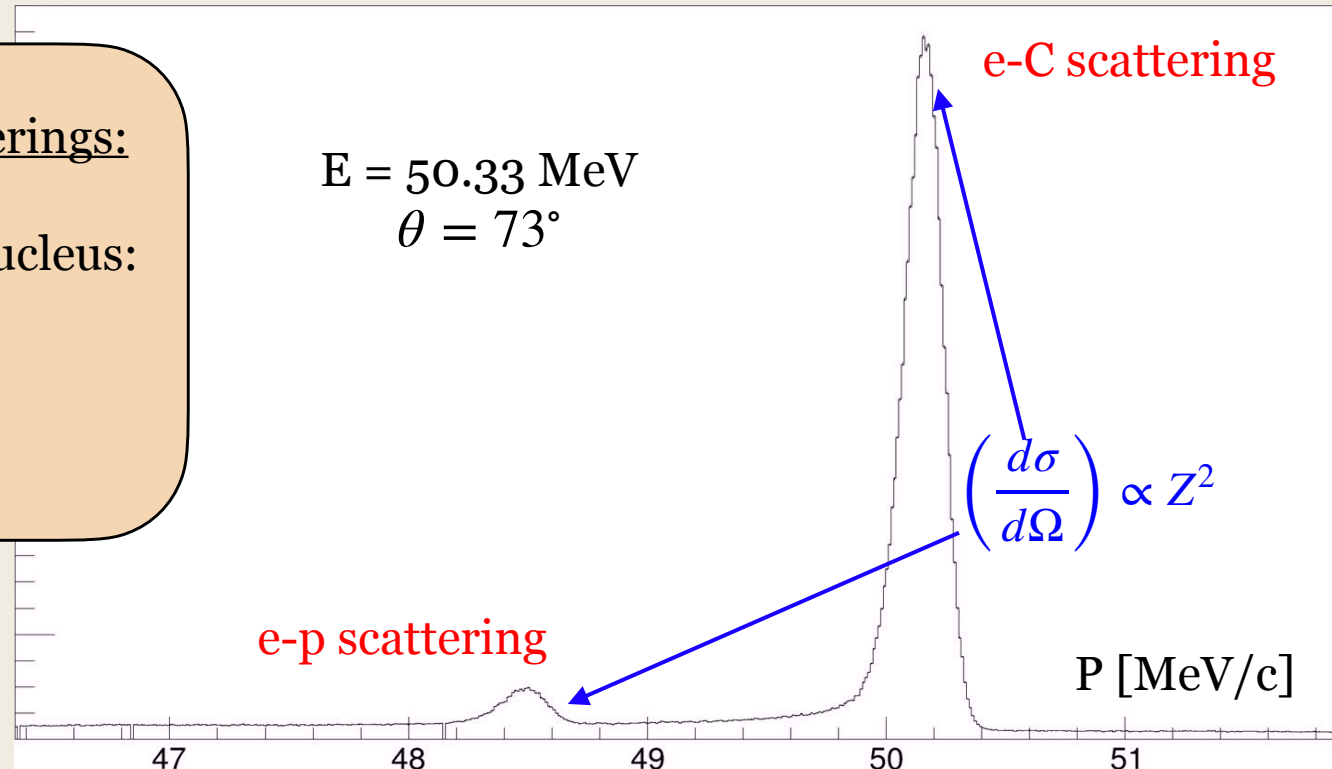
|                  | Energy [GeV] | Angle [°] | $Q^2$ [(GeV/c) <sup>2</sup> ] |
|------------------|--------------|-----------|-------------------------------|
| Mainz            | 0.18-0.855   | 15-130    | 0.004-1.0                     |
| PRad             | 1.1 & 2.2    | 0.7-7.0   | 0.0002-0.06                   |
| ULQ <sup>2</sup> | 0.01-0.06    | 30-150    | 0.0003-0.008                  |

# Absolute cross-section measurement

Simultaneous detection of e-p and e-C scatterings:

- Use of a CH<sub>2</sub> target.
- Momentum of a scattered electron on a X nucleus:

$$P'_X \sim \frac{E}{1 + \frac{2E \sin^2 \theta/2}{M_X}}$$



Simultaneous detection of e-p and e-C scattering with a CH<sub>2</sub> target (Experimental data).

# Absolute cross-section measurement

Absolute cross-section of e+p scattering:

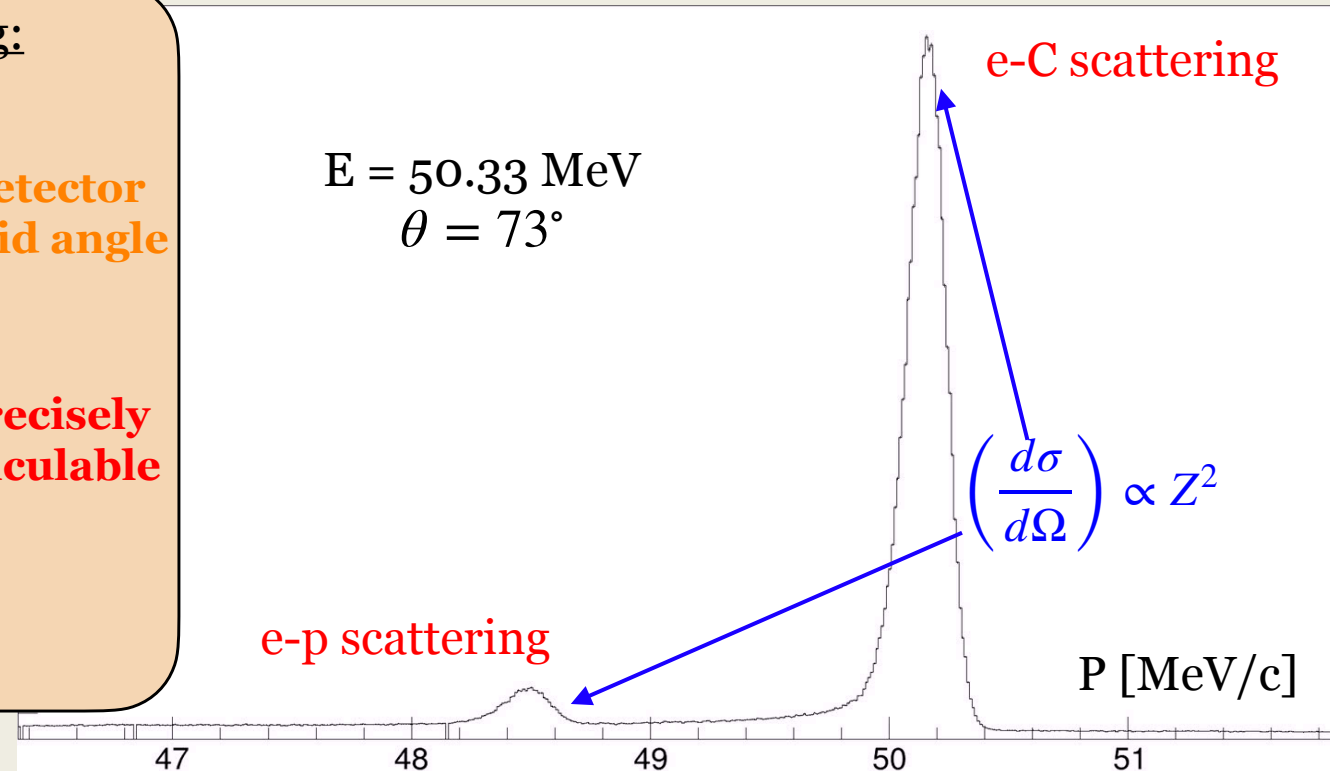
$$\left(\frac{d\sigma}{d\Omega}\right)_{e-p} = \frac{\text{Event number } N_{e-p}}{\text{Beam dose } N_e \times \text{Target number } N_p \times \text{Detector solid angle } \Delta\Omega}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-p} = \frac{N_{e-p}/N_{e-C}}{N_p/N_C} \left(\frac{d\sigma}{d\Omega}\right)_{e-C}$$

Precisely calculable

Ratio of H and C nuclei

**Required for precise measurement!**



Simultaneous detection of e-p and e-C scattering with a CH<sub>2</sub> target (Experimental data).

# III. The ULQ<sup>2</sup> experiment

# Research center for Accelerator and RadioIsotope Science (RARiS)



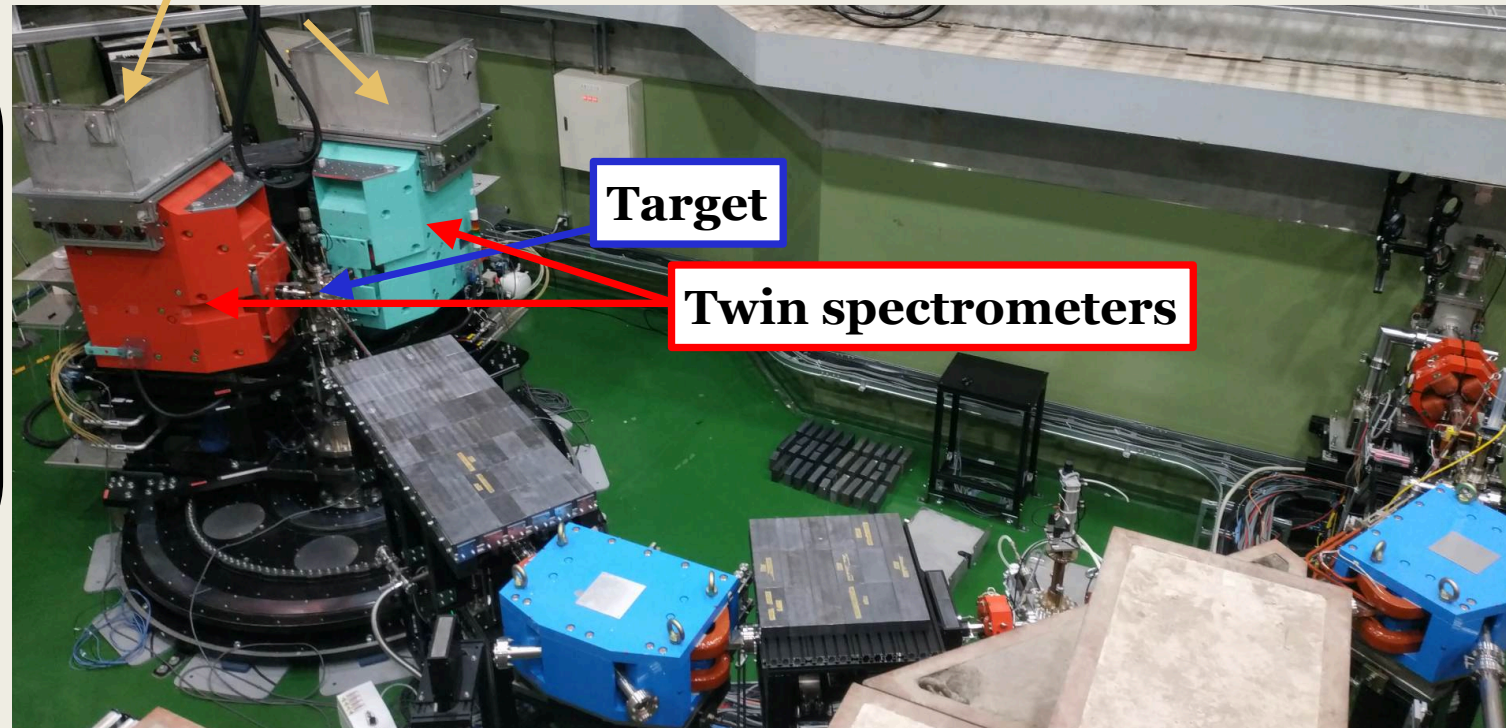
# Beam line



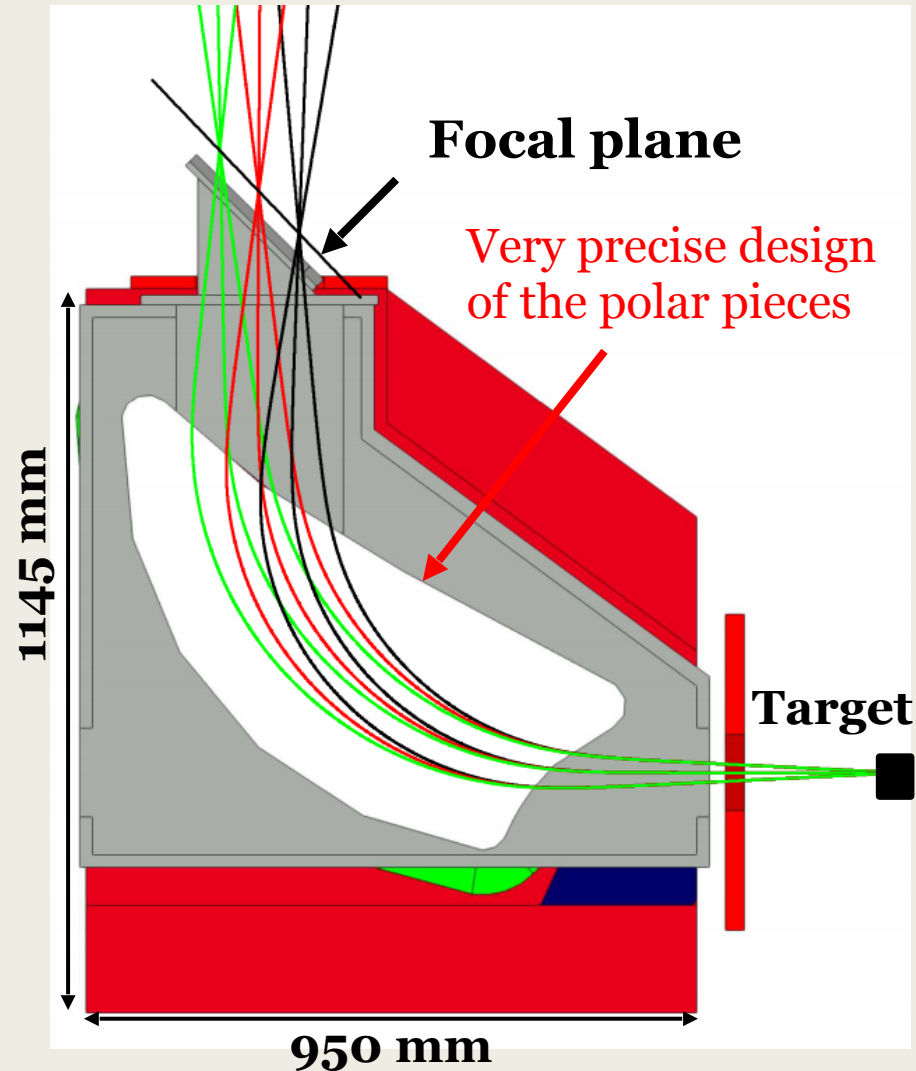
**Detectors**

## ULQ<sup>2</sup> accelerator:

- Energy:  $E = 10 - 60 \text{ MeV}$
- Energy spread:  $\sigma_E/E \sim 0.1\%$
- Position spread:  $\sigma_x, \sigma_y \sim 1 \text{ mm}$
- Intensity:  $I \leq 1 \mu\text{A}$
- Pulse duration:  $\Delta t \sim 3 \mu\text{s}$
- Pulse frequency:  $f = 1-300 \text{ Hz}$



# Spectrometers



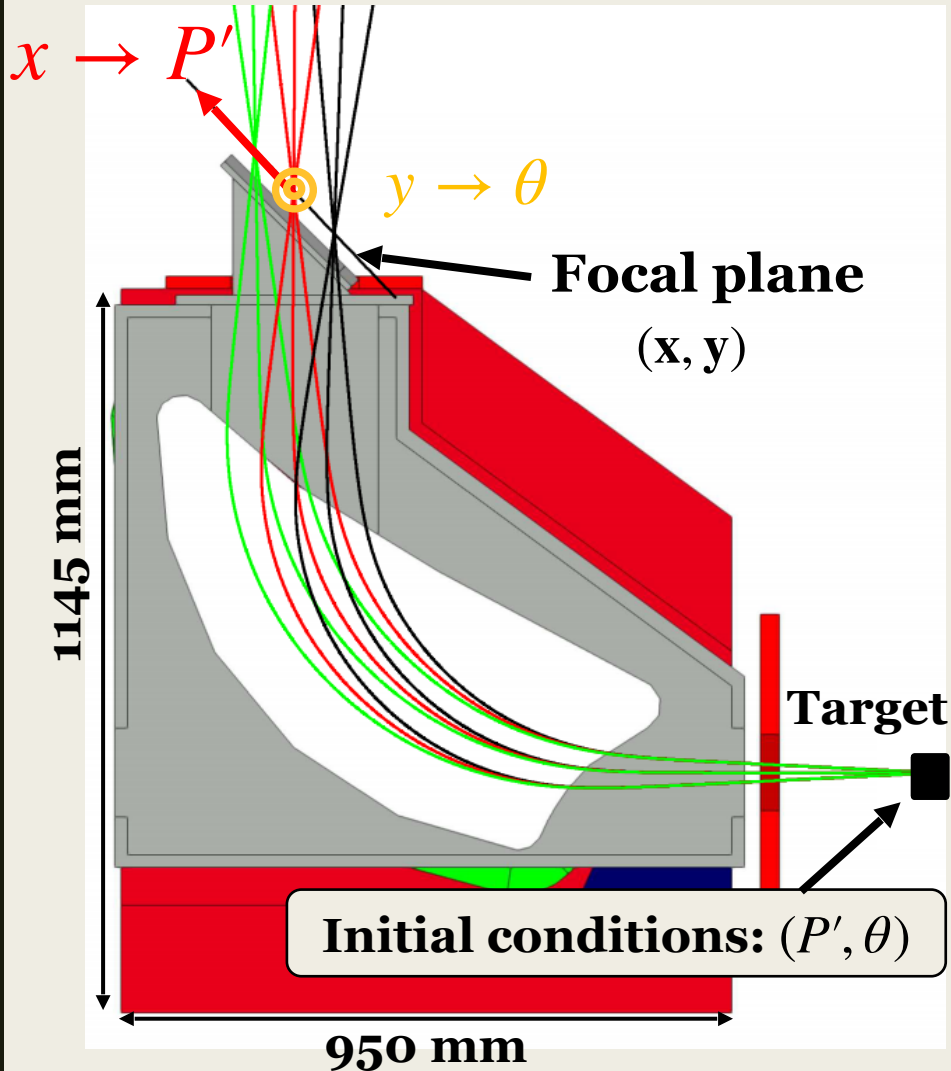
Spectrometer 1 → Data taking

Spectrometer 2 → Target monitor

## Measurement in the focal plane:

- ❑ ULQ<sup>2</sup> experiment uses very low energy electrons.
  - ➔ Strong multiple scattering:  $\langle \theta_{MS} \rangle \propto \frac{1}{P'}$
  - ➔ Impossible to determine the path of the electrons.
- ❑ Single measurement of the electron position in the focal plane.
- ❑ Connected to the target chamber and under vacuum ( $< 1$  mPa).

# Spectrometers

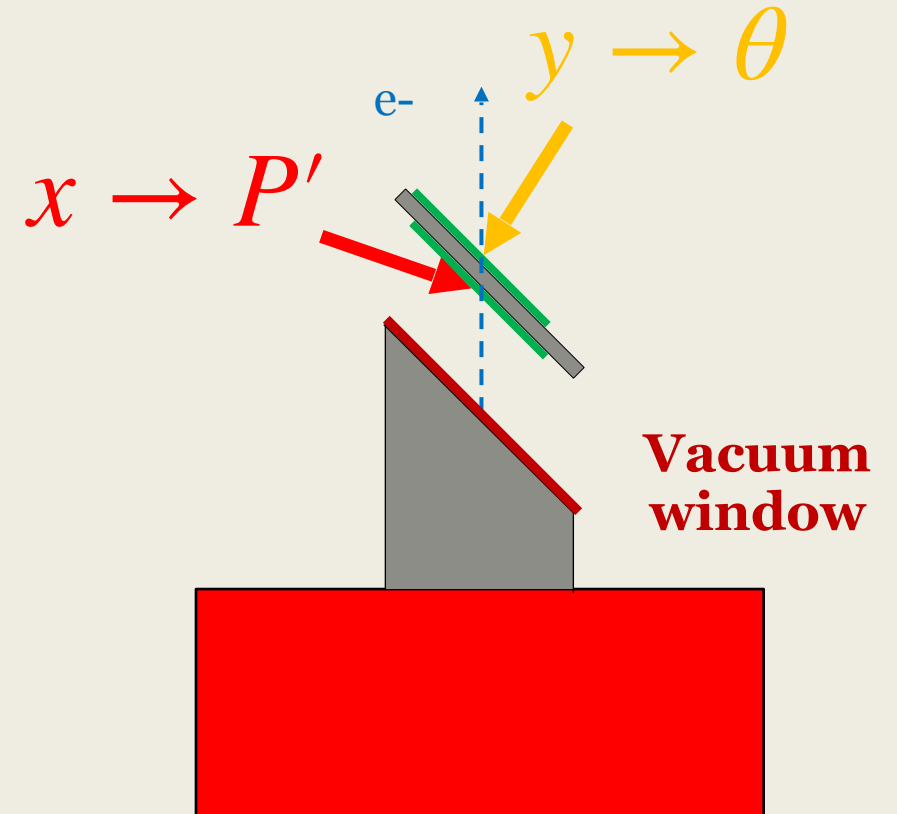
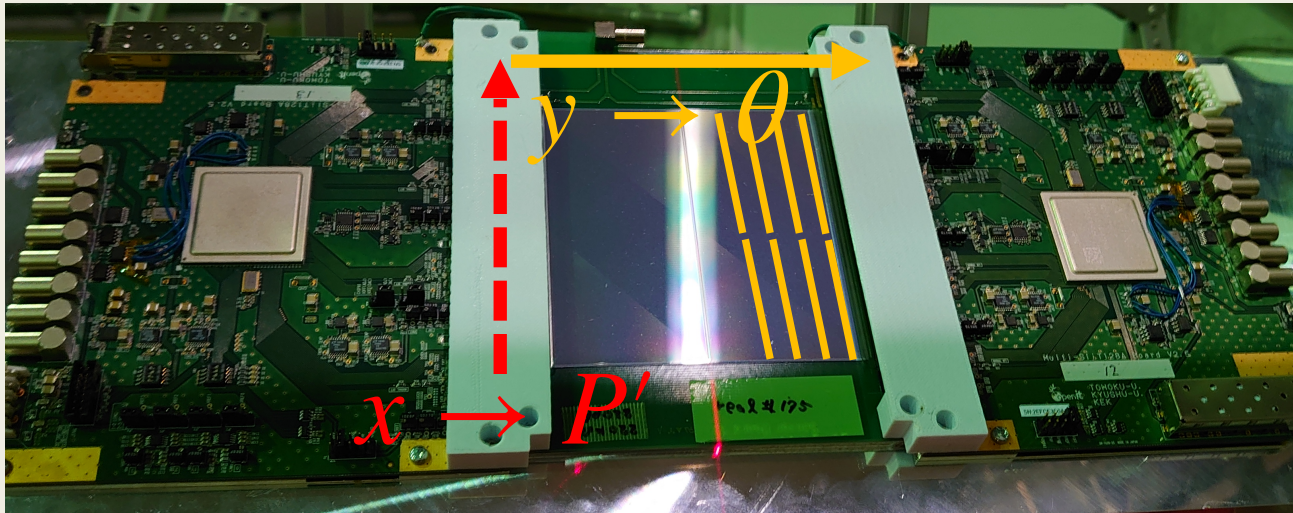


## Measurement in the focal plane:

- ❑ Electrons focused in the focal plane depending on their momentum  $p$  and horizontal scattering angle  $\theta$ .
- ❑  $(P', \theta)$  determined from the  $(x, y)$  position of the electrons on the detectors placed in the focal plane.
- ❑ To resolve e-p and e-C scattering peaks at  $Q^2 = 0.0003 \text{ (GeV/c)}^2$ ,

$$\text{Momentum resolution: } \sigma_p = \frac{\Delta P}{P} < 10^{-3}$$

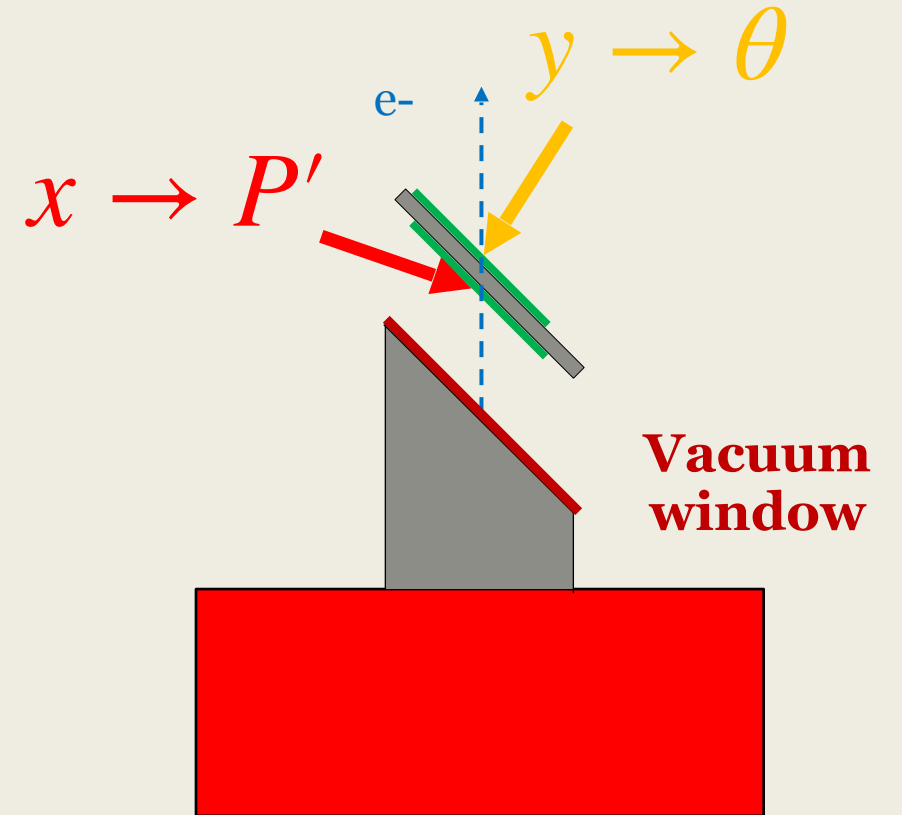
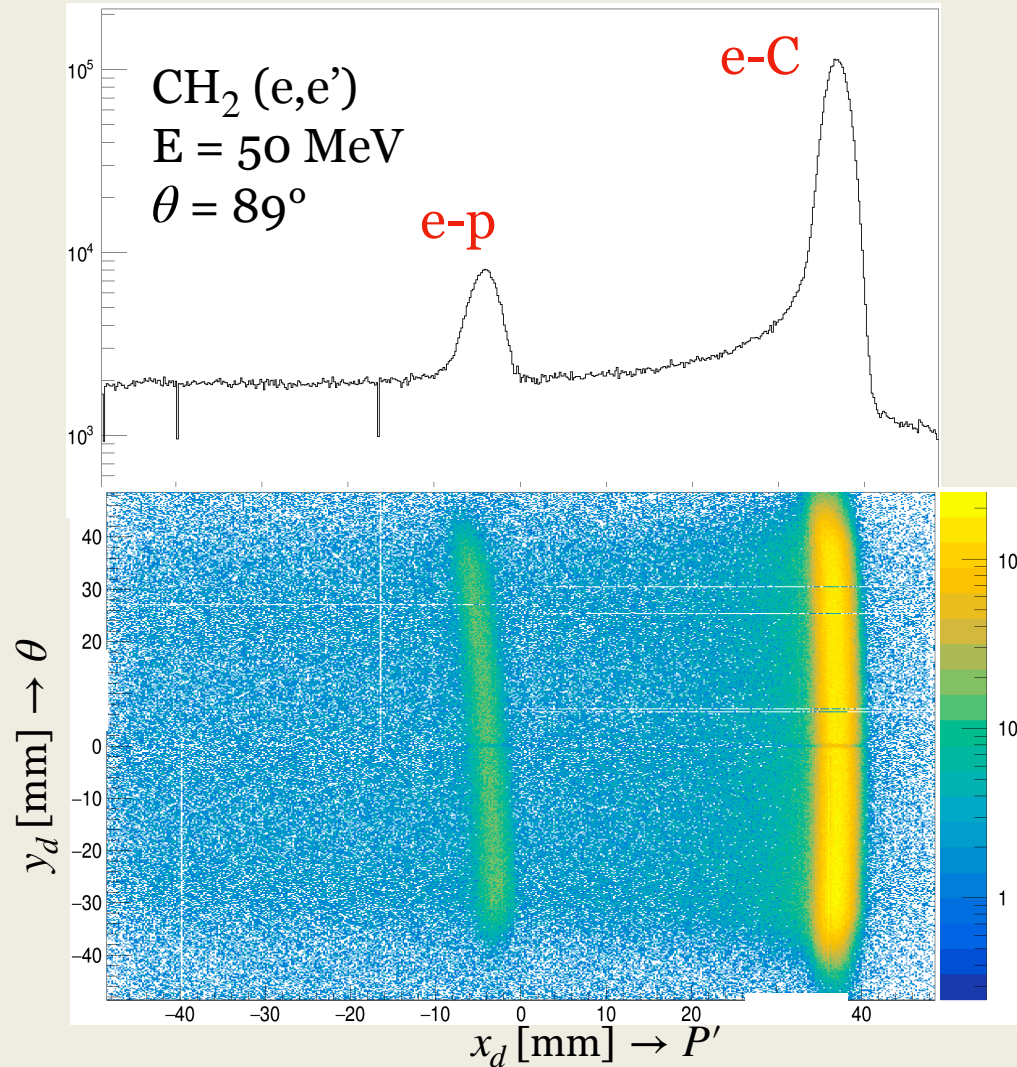
# Detection system



## Single Sided Silicon Strip Detectors (SSSDs):

- Developed with the J-PARC muon g-2/EDM collaboration.
- 2 detectors each made of 2 x 512 channels on each spectrometer.
- Located in the focal plane of the spectrometers.
- Channel width: 0.19 mm, thickness: 0.32 mm.

# Detection system



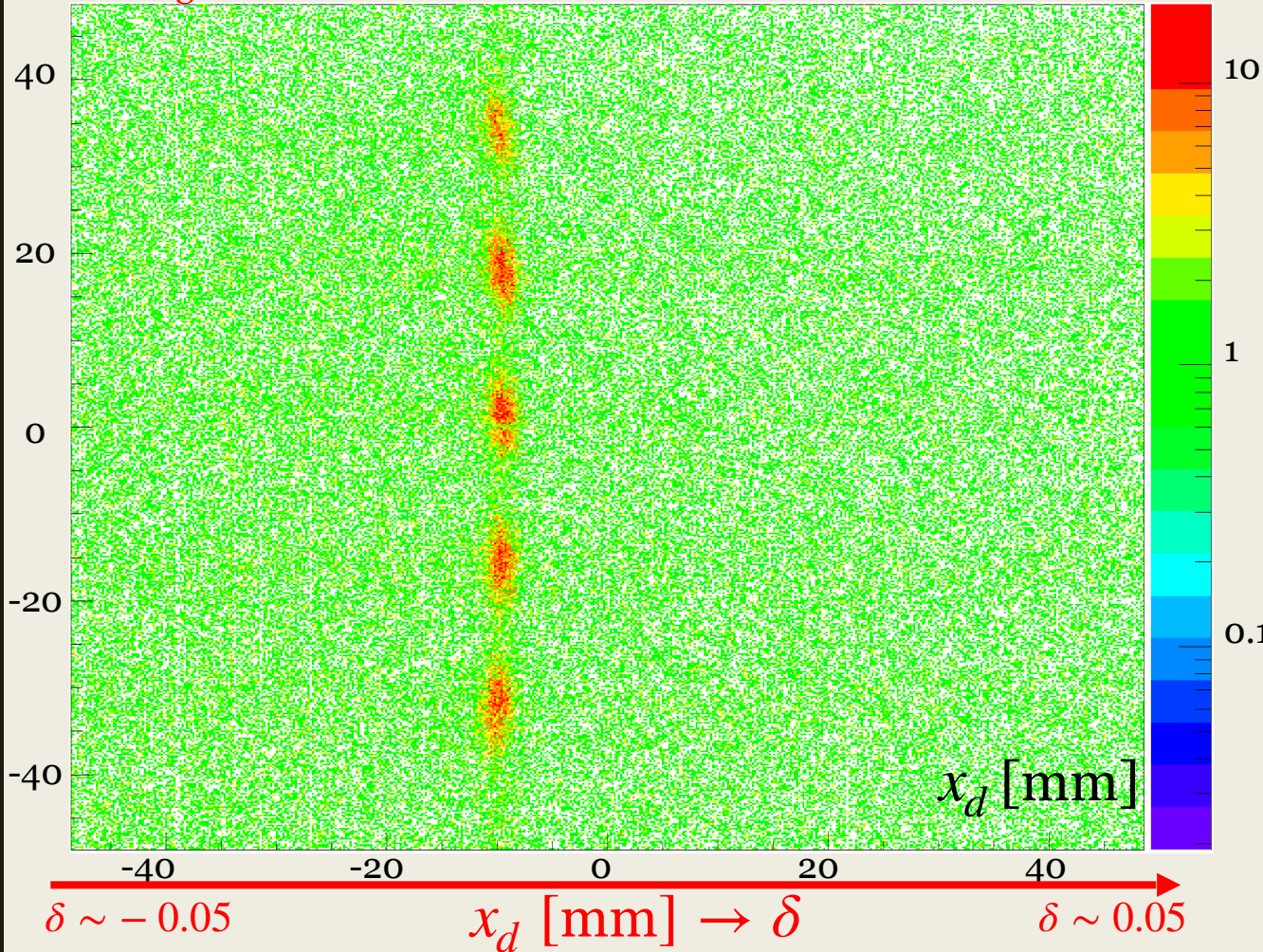
# Spectrometer optics

Momentum dispersion Angular dispersion

Spectrometer central angle

Data taken with a sieve slit

$y_d$  [mm]  $\rightarrow \Delta\theta = \theta - \theta_s$

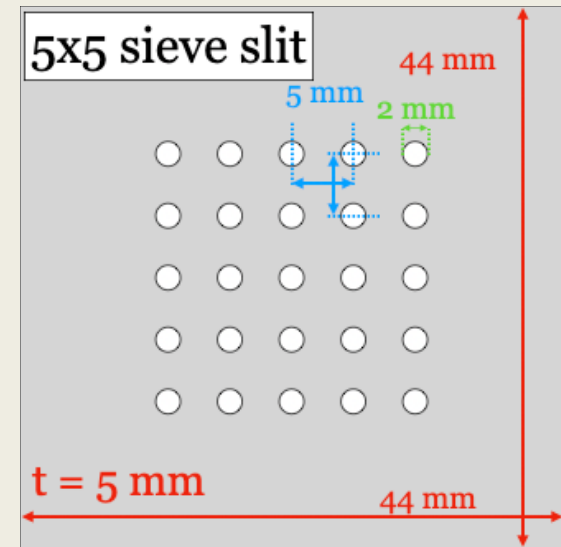


Relation between  $(x_d, y_d)$  and  $(P', \theta)$ :

$$x_d = (x_d | \delta) \delta + \dots$$

$$y_d = (y_d | \Delta\theta) \Delta\theta + \dots$$

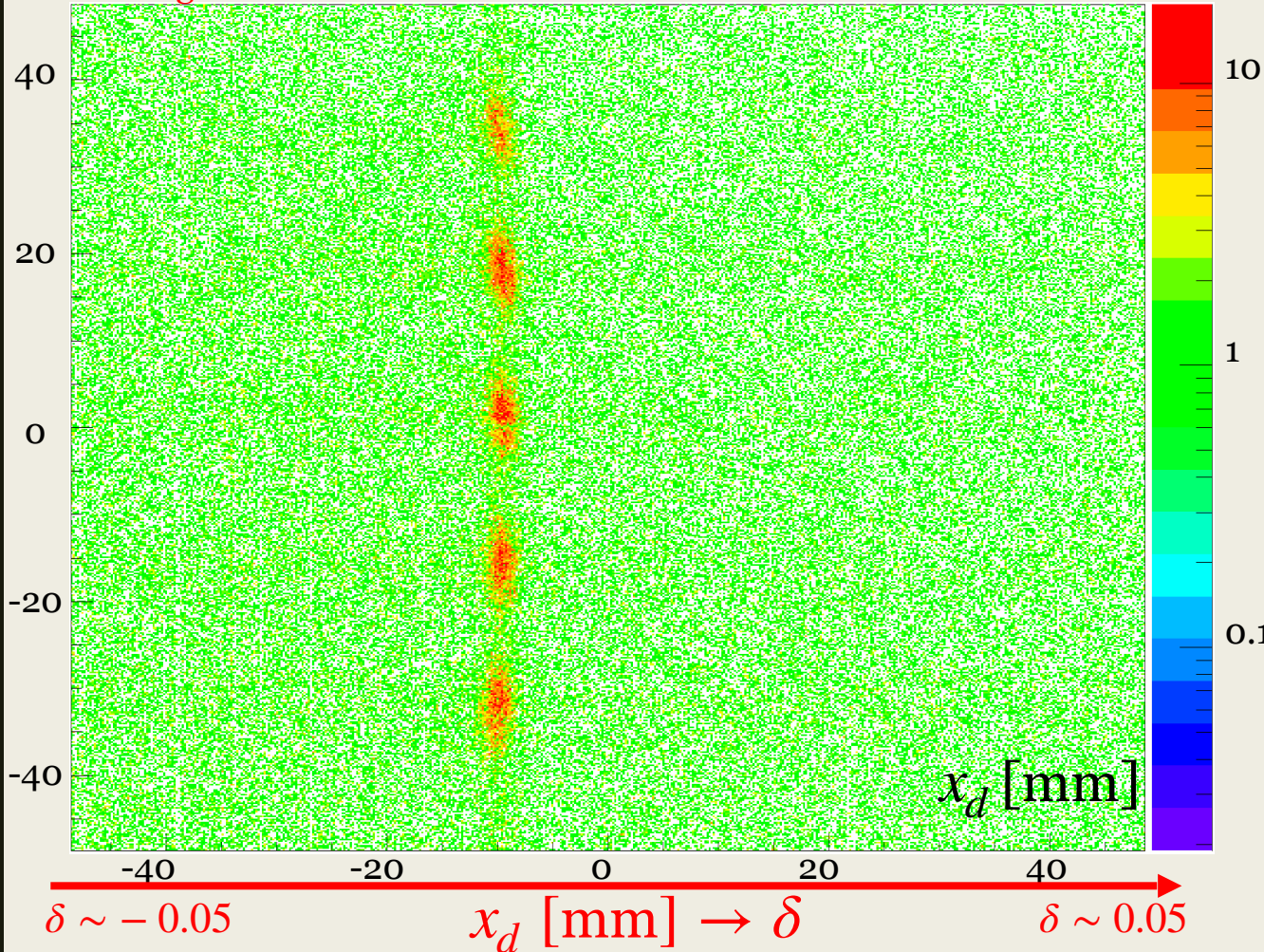
with  $\delta = \frac{P' - P_c}{\propto B_C P_c}$  Spectrometer central momentum



# Spectrometer optics

Spectrometer  
central angle

Data taken with a sieve slit



Momentum dispersion Angular dispersion

Relation between  $(x_d, y_d)$  and  $(P', \theta)$ :

$$x_d = (x_d | \delta) \delta + \dots$$

$$y_d = (y_d | \Delta\theta) \Delta\theta + \dots$$

with  $\delta = \frac{P' - P_c}{\propto B_C P_c}$  Spectrometer central momentum

Measured before each experiment

Commissioning results:

$$(x_d | \delta) = 864(0.1) \text{ mm}$$

$$(y_d | \Delta\theta) = 1.000(4) \text{ mm/mrad}$$

$$\sigma_p = \frac{\Delta p}{p} = 5.6 \times 10^{-4}$$

→ High resolution spectrometers!

# Q<sup>2</sup> determination

- From  $x_d$ , we get  $\delta$  but not directly  $P'$  ...
- The beam energy derived from the current of upstream magnets is not precise enough ...
- To get E and  $P'$ , use of C and H peaks:

$$x_X \sim (x_d | \delta) \frac{P'_X - P_c}{P_c}$$

1<sup>st</sup> order

$$R \equiv \frac{P'_C}{P'_H} \sim 1 + \frac{x_C - x_H}{(x_d | \delta)}$$

$$P'_X \stackrel{\text{URL}}{\sim} \frac{E}{1 + \frac{2E \sin^2 \theta/2}{M_X}}$$

$$R \equiv \frac{P'_C}{P'_H} \sim 1 + 2E \sin^2 \theta/2 \left( \frac{1}{M_H} - \frac{1}{M_C} \right)$$

Determination of the beam energy directly from the experimental data!

➔ **Precise determination of Q<sup>2</sup>!**

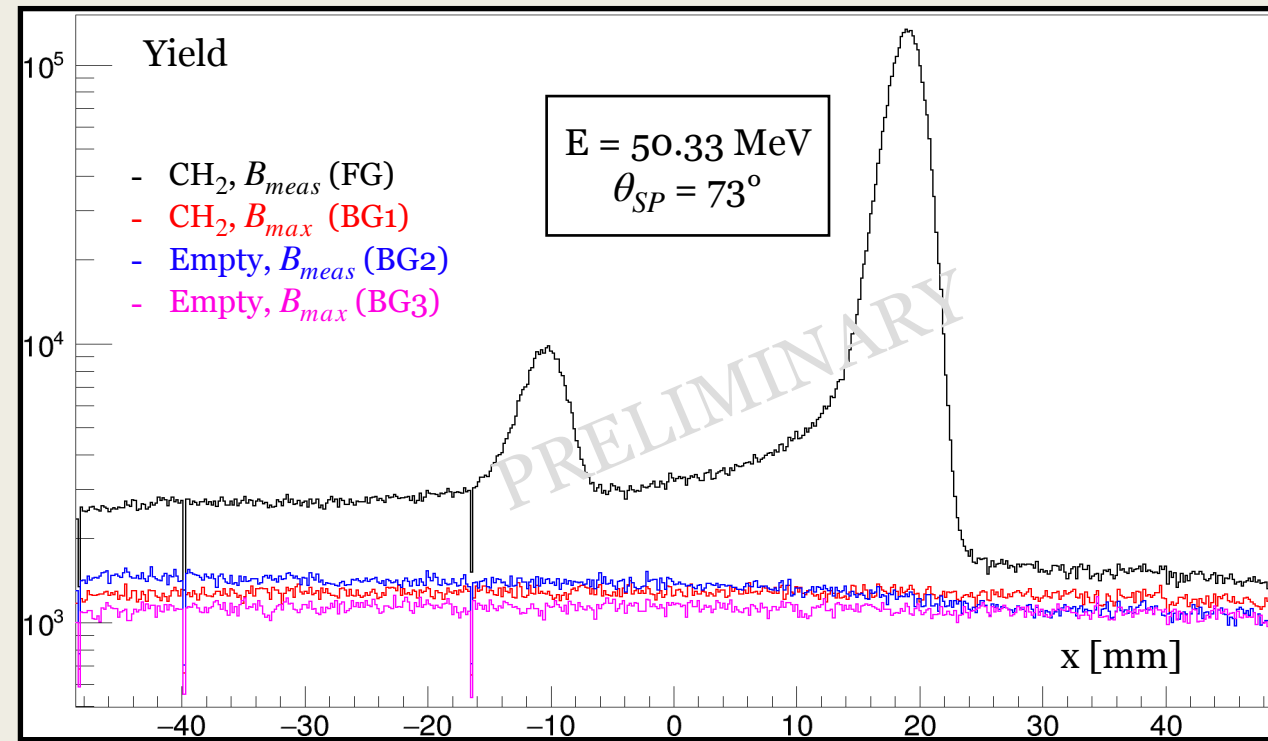
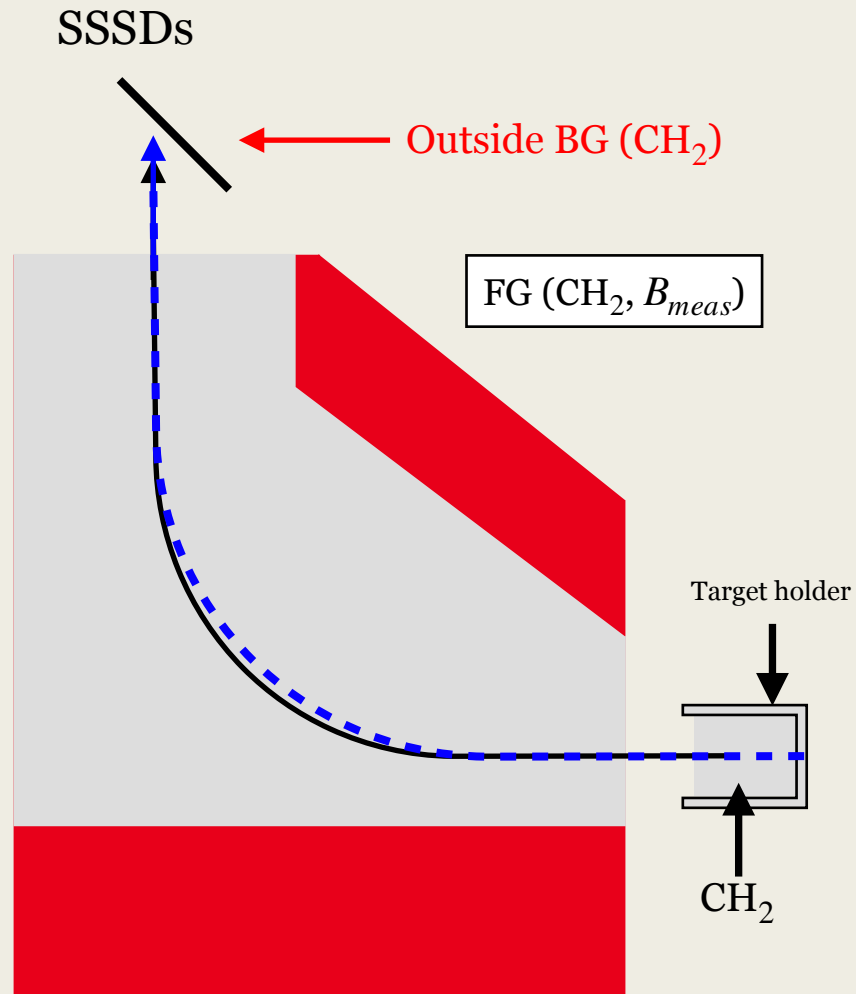


IV.

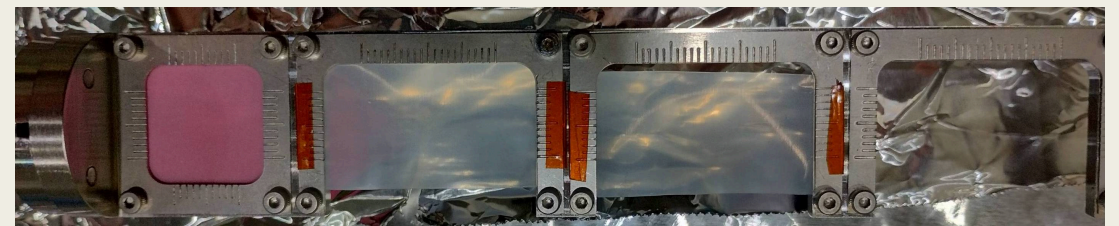
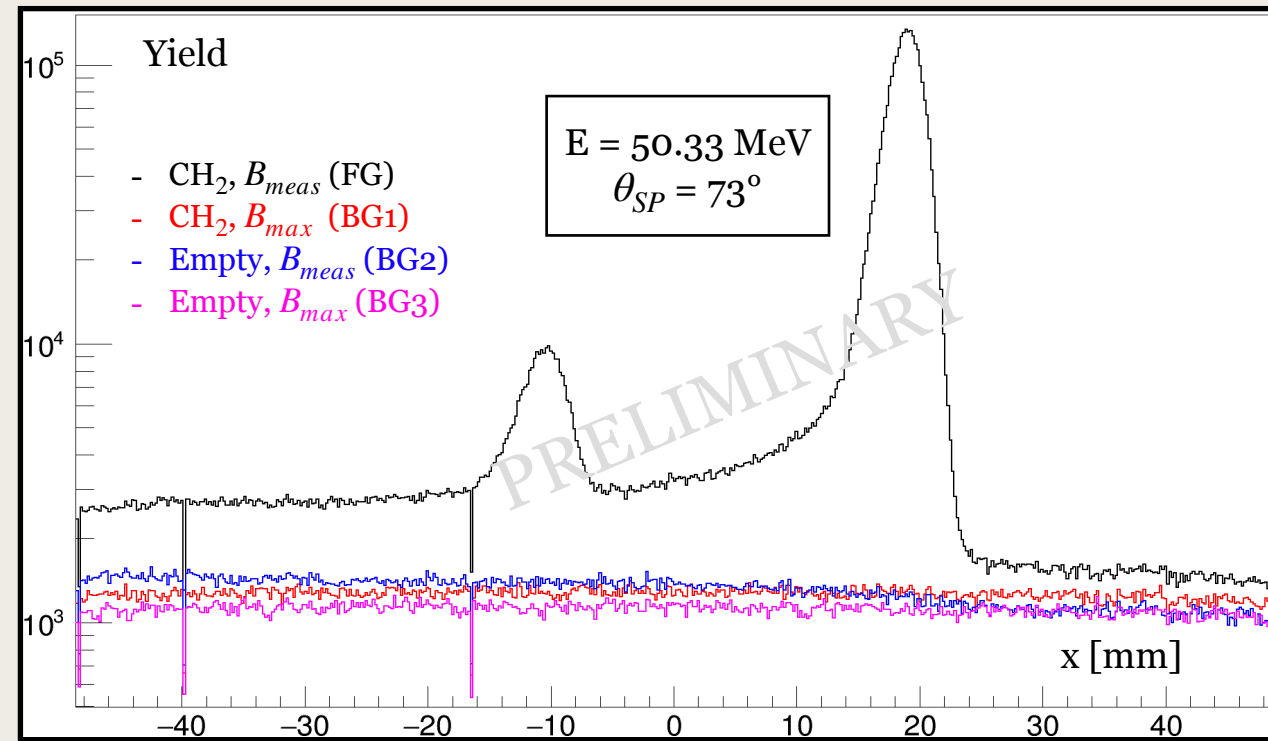
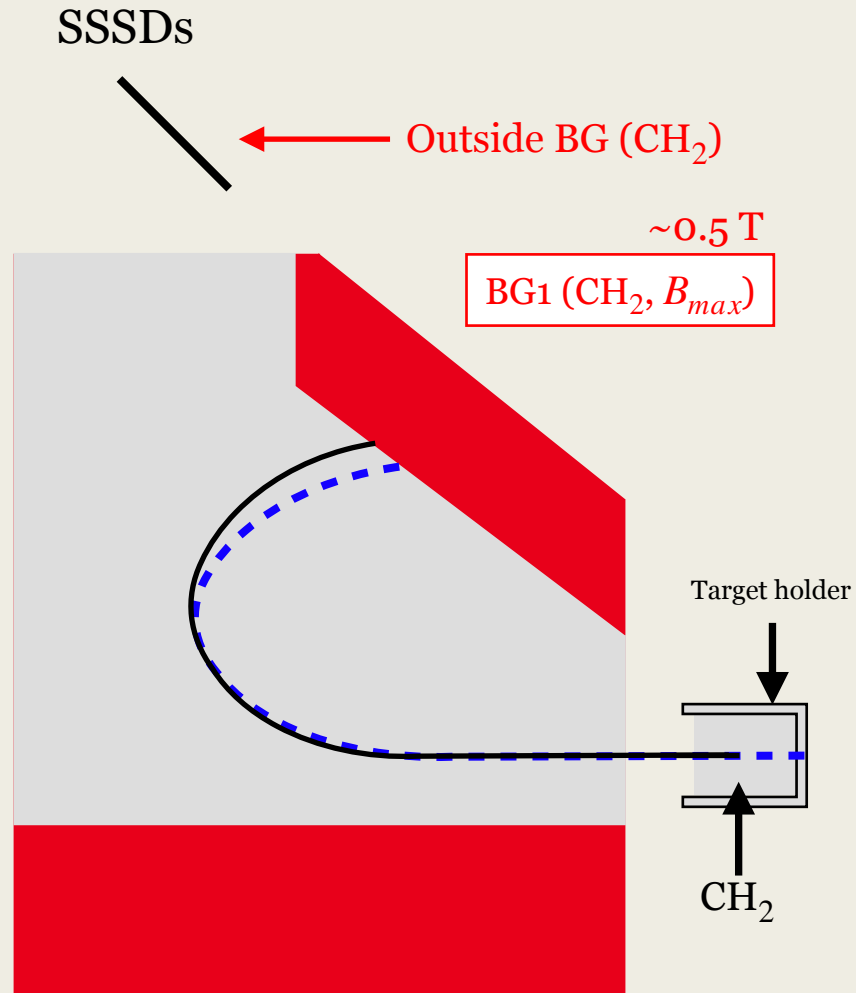
# Data taking



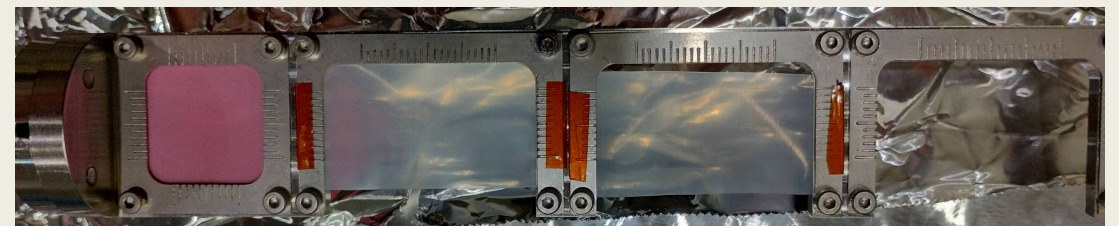
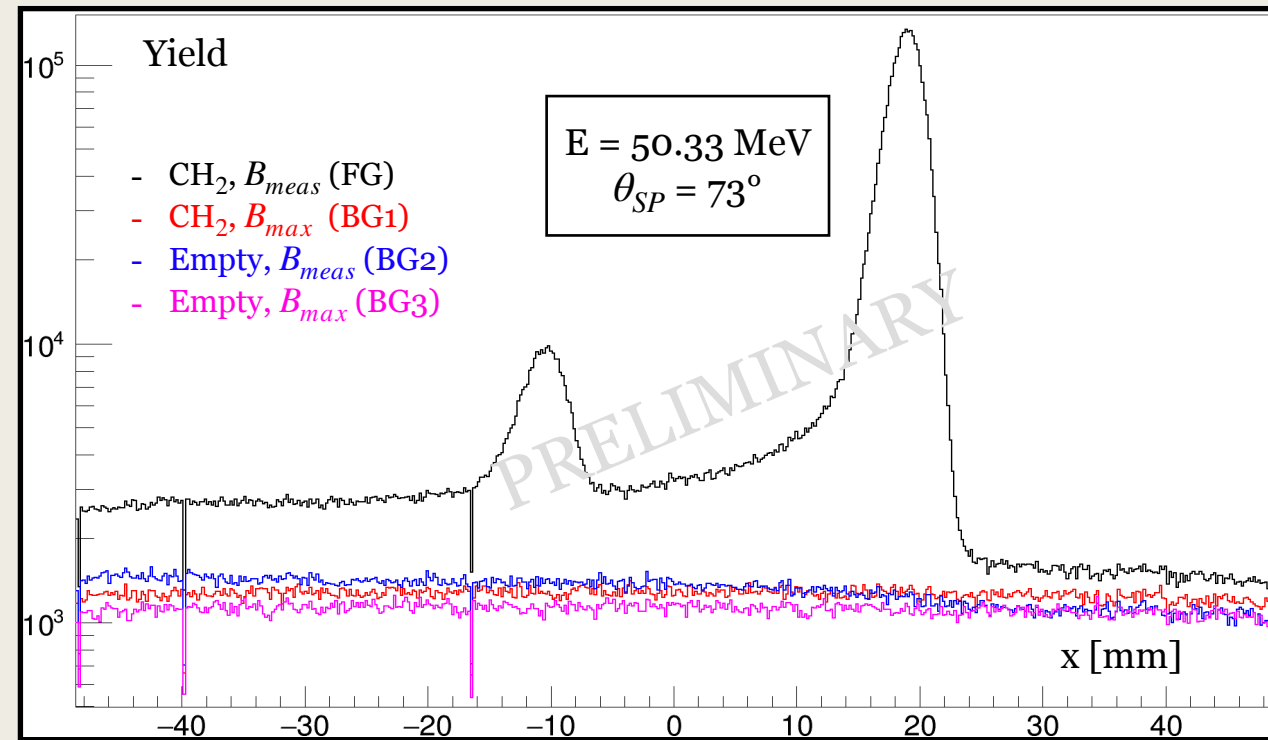
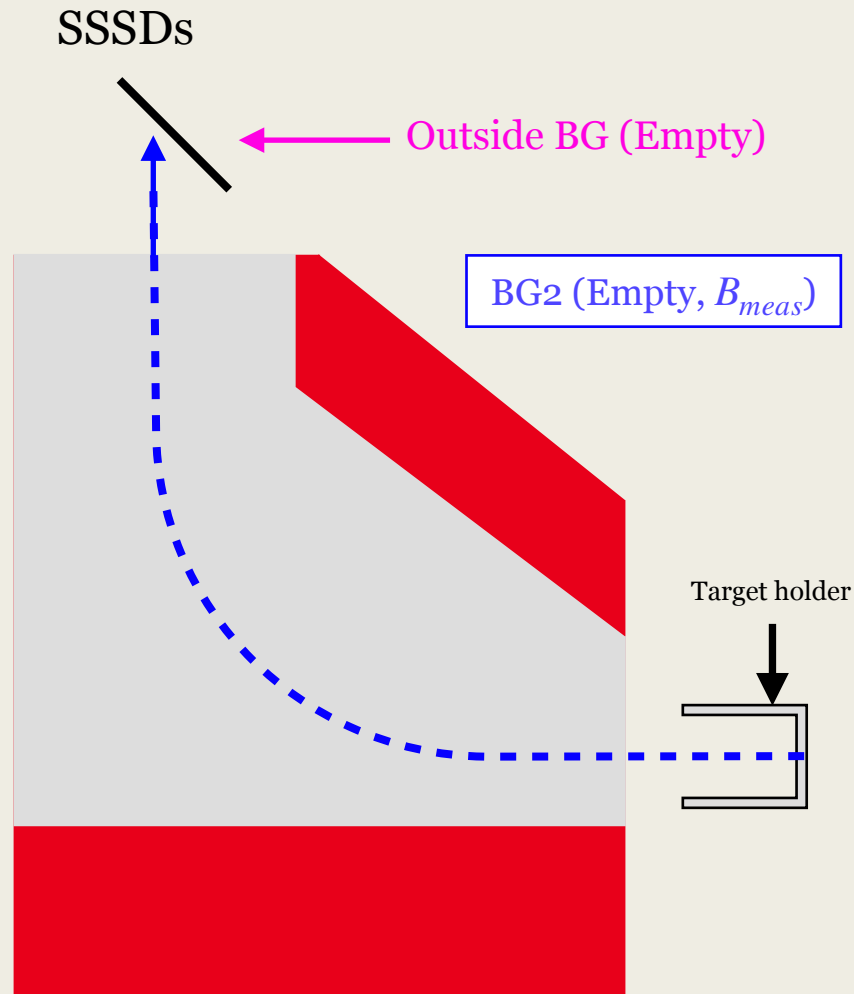
# Measurement



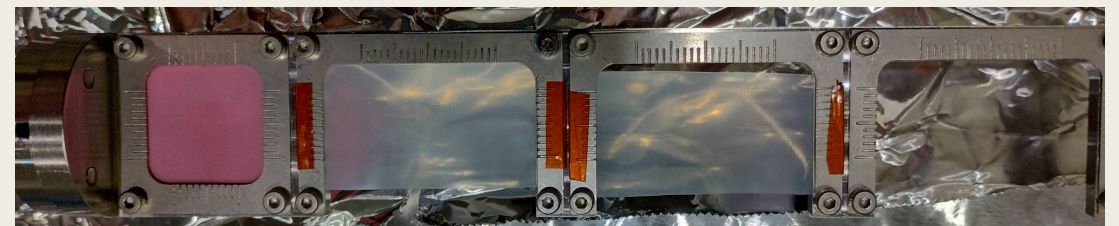
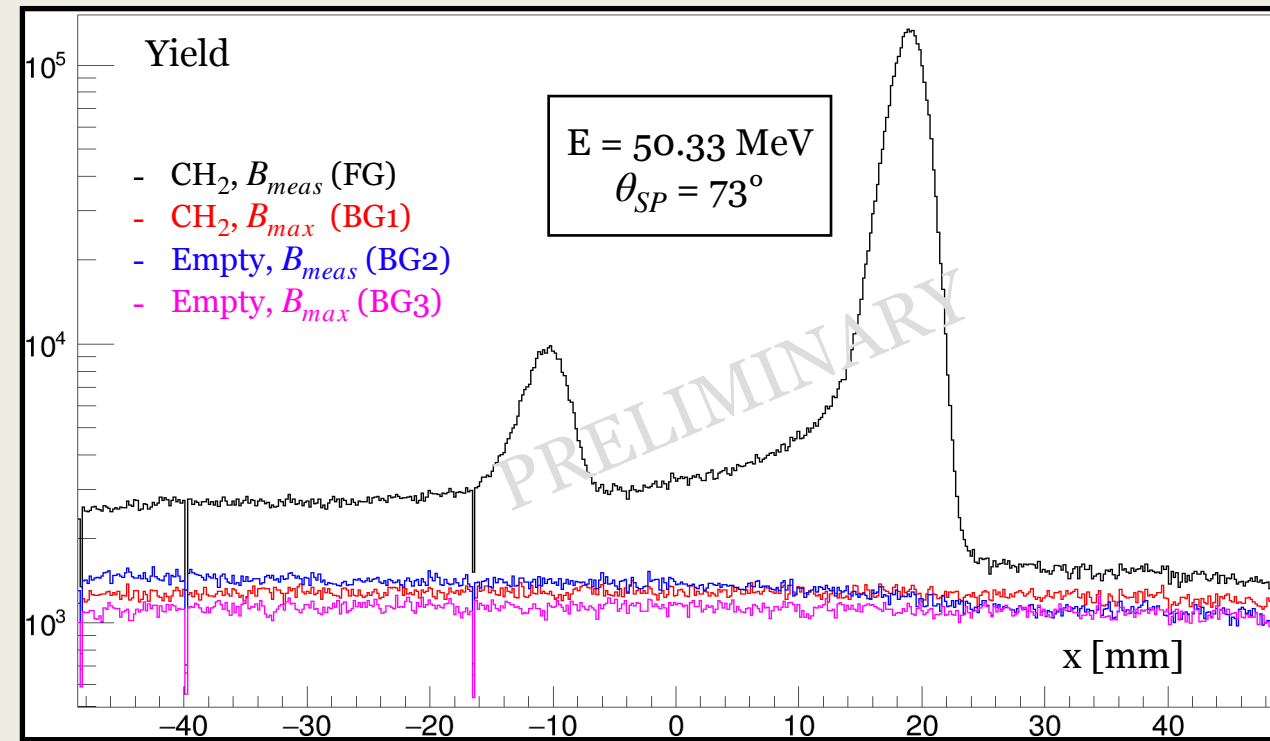
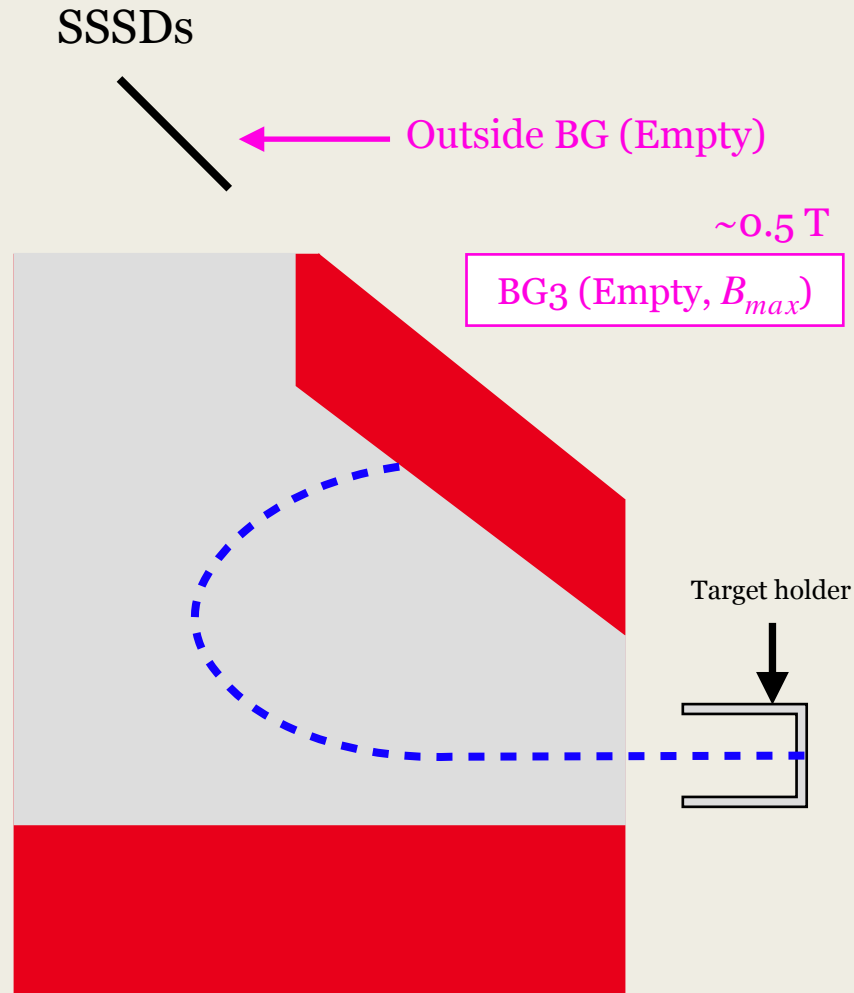
# Measurement



# Measurement



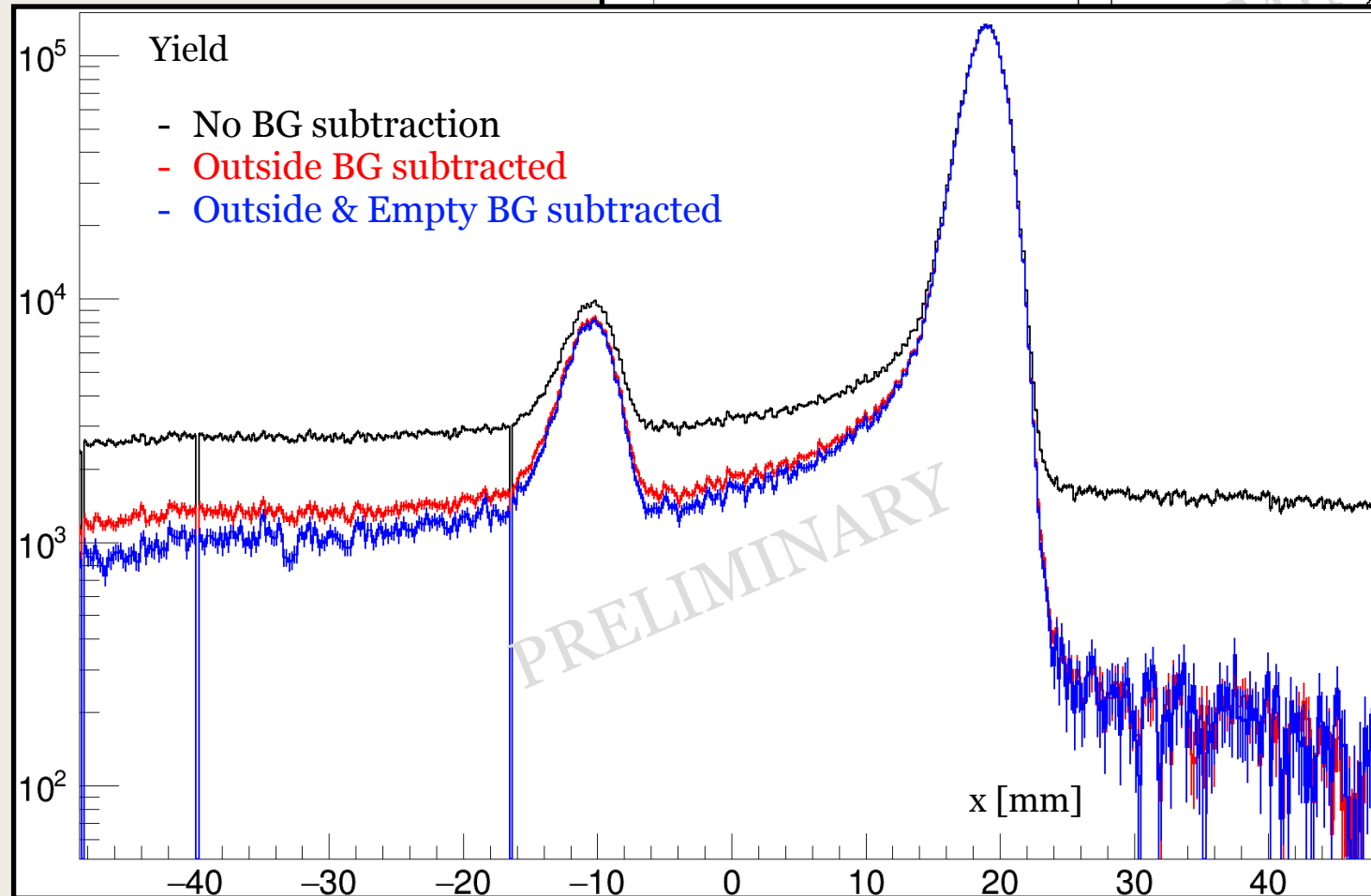
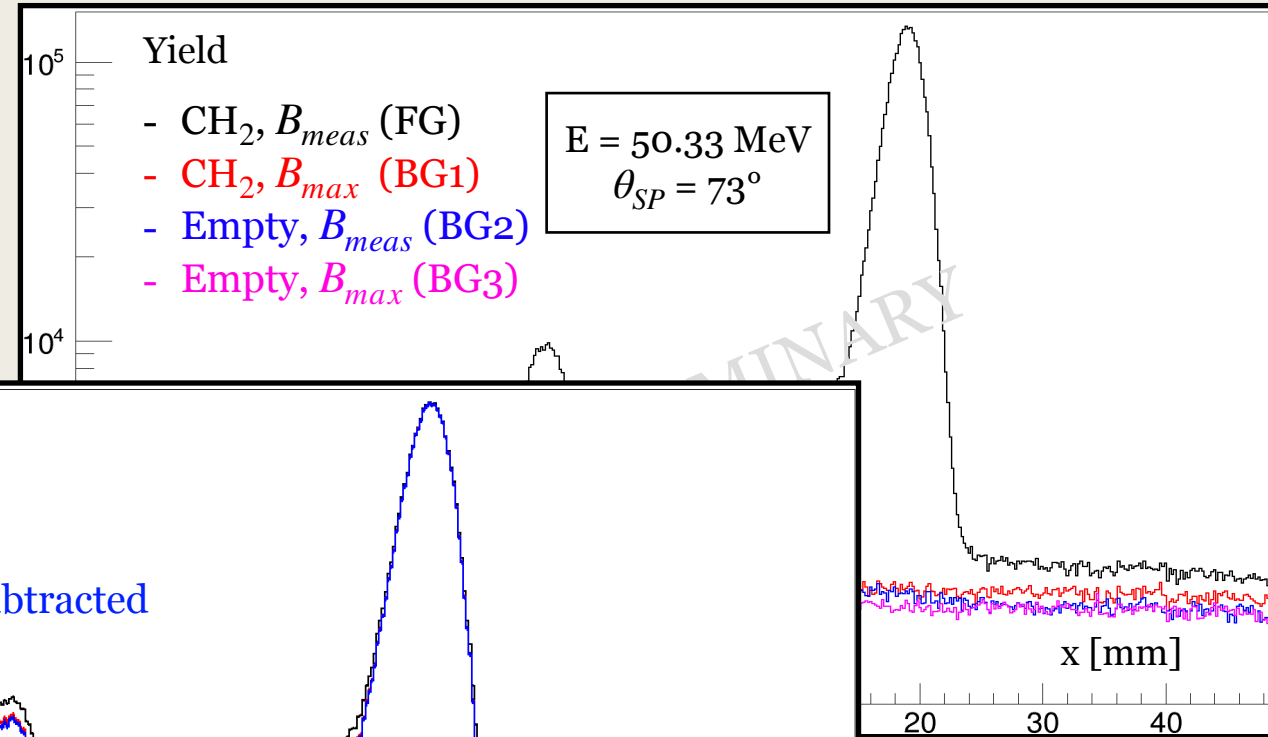
# Measurement



# Measurement

Outside BG (red)      BG from target holder (blue)

$$[\text{FG} + \text{BG1}] - [\text{BG2} + \text{BG3}]$$





V.

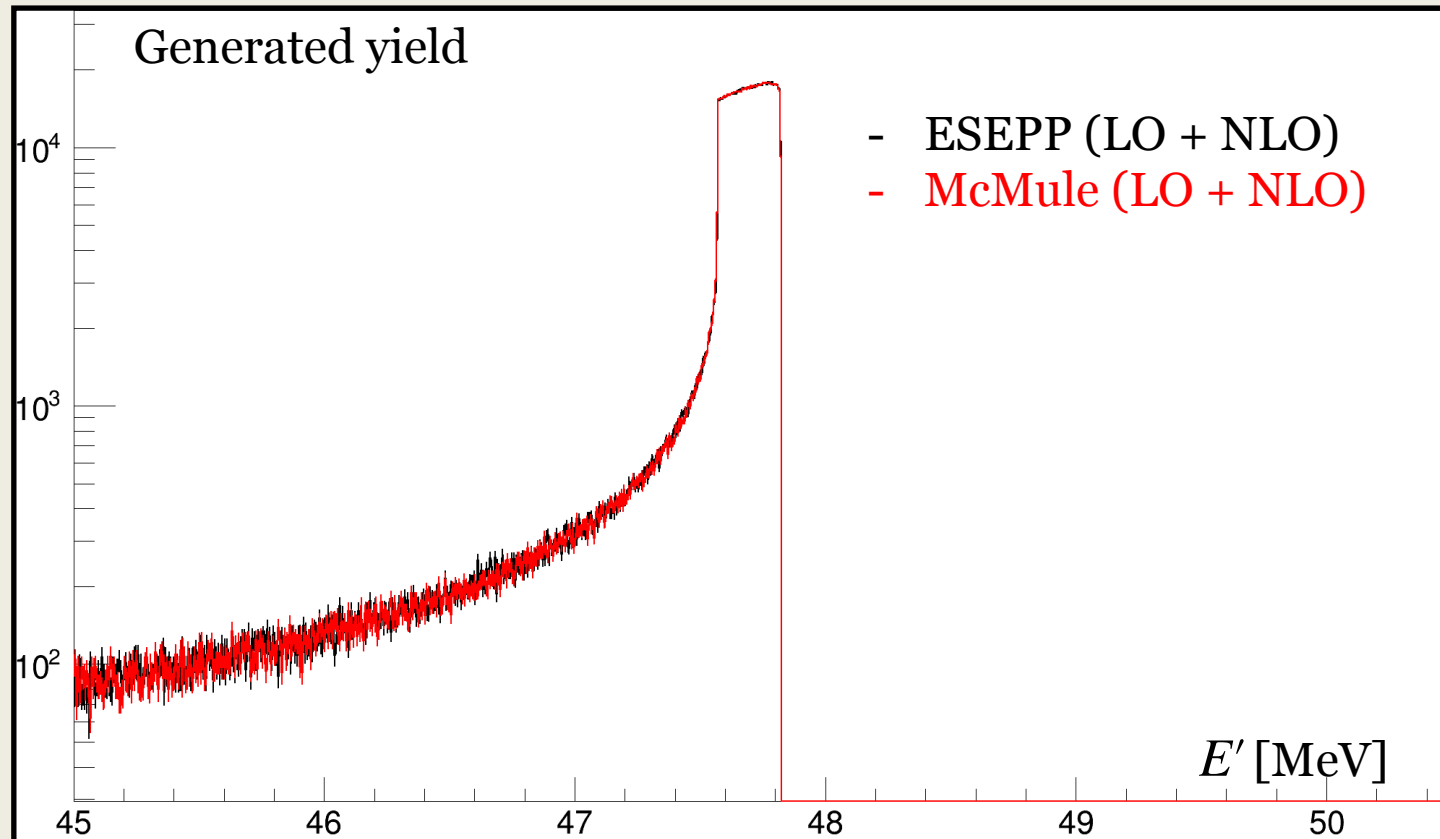
# Data analysis



# Simulation

P. Banerjee *et al.*, SciPost Phys. **9**, 027 (2020).

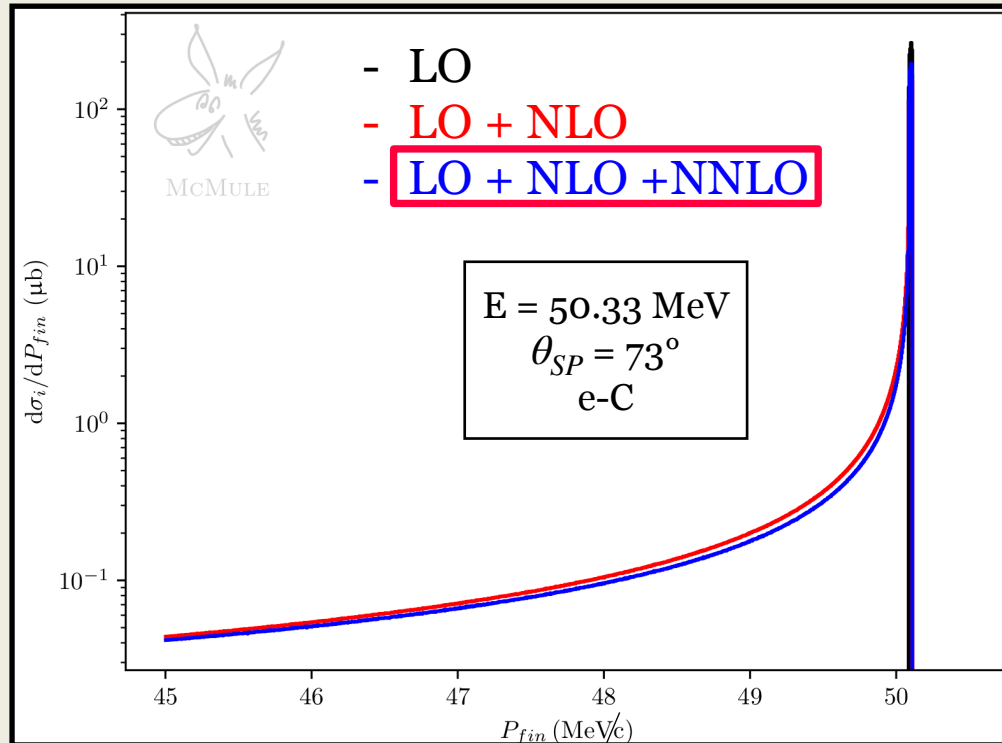
- McMule for e-H & e-C calculation of LO, NLO & NNLO!



# Simulation

P. Banerjee *et al.*, SciPost Phys. **9**, 027 (2020).

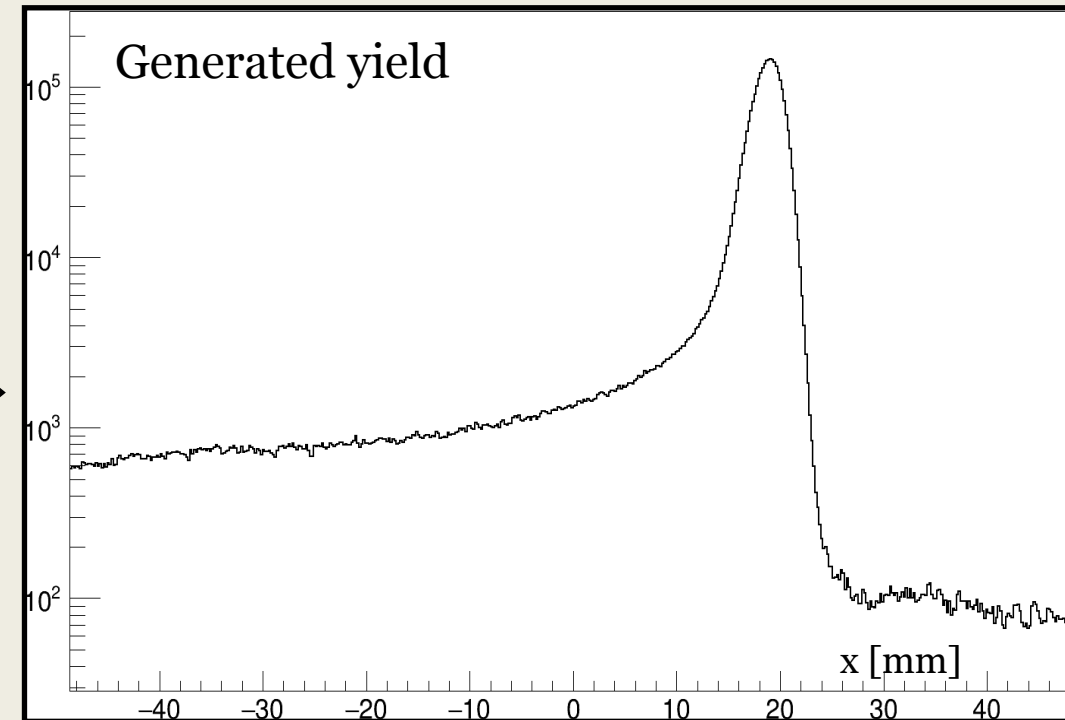
- McMule for e-H & e-C calculation of LO, NLO & **NNLO!**



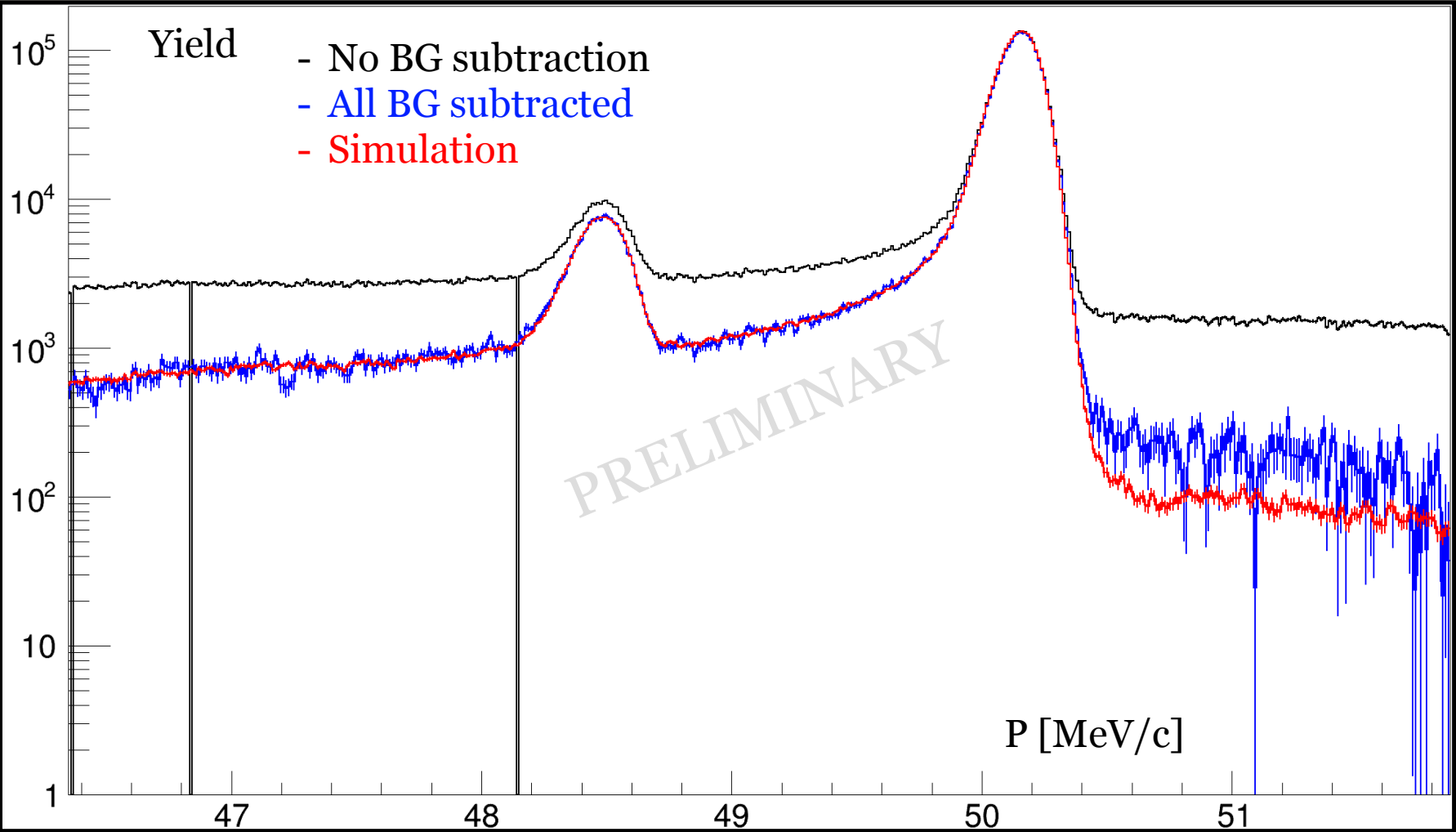
Add beam  
momentum  
distribution



Geant4  
simulation

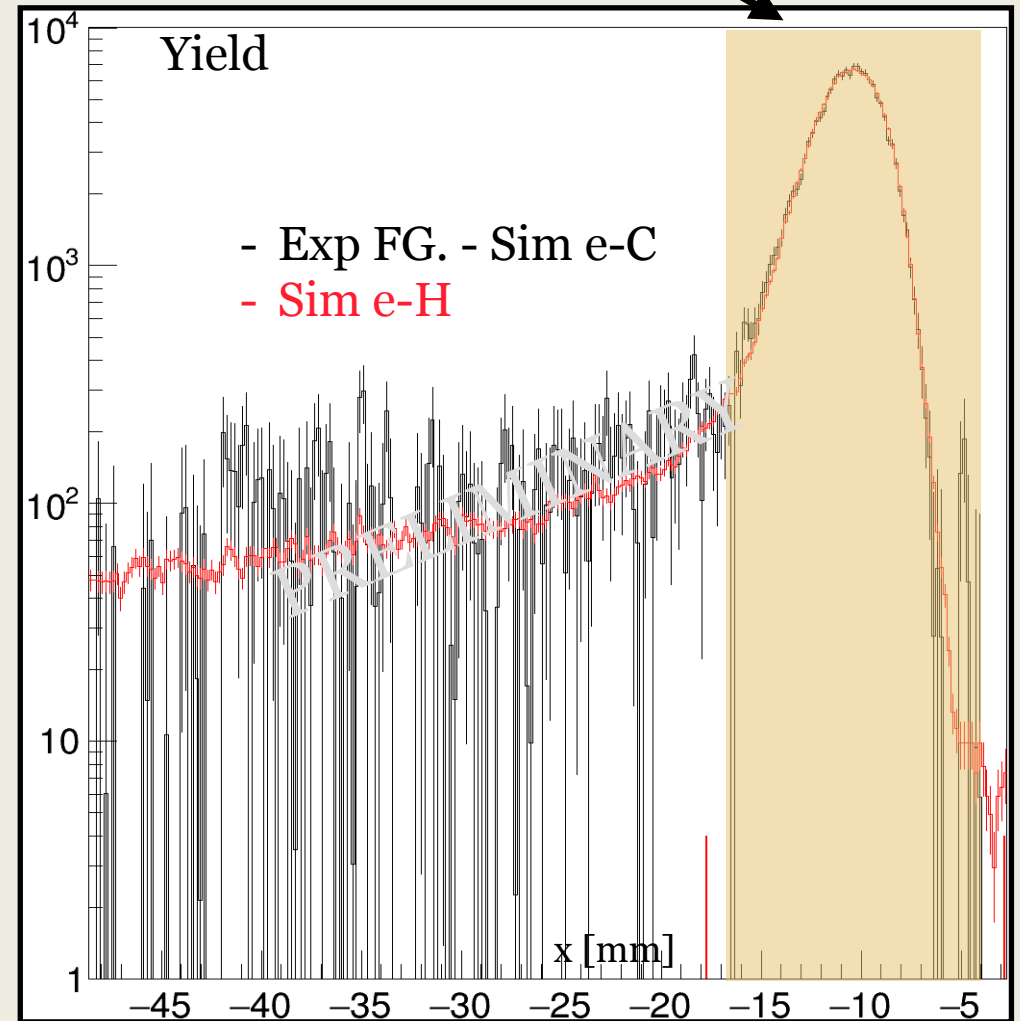
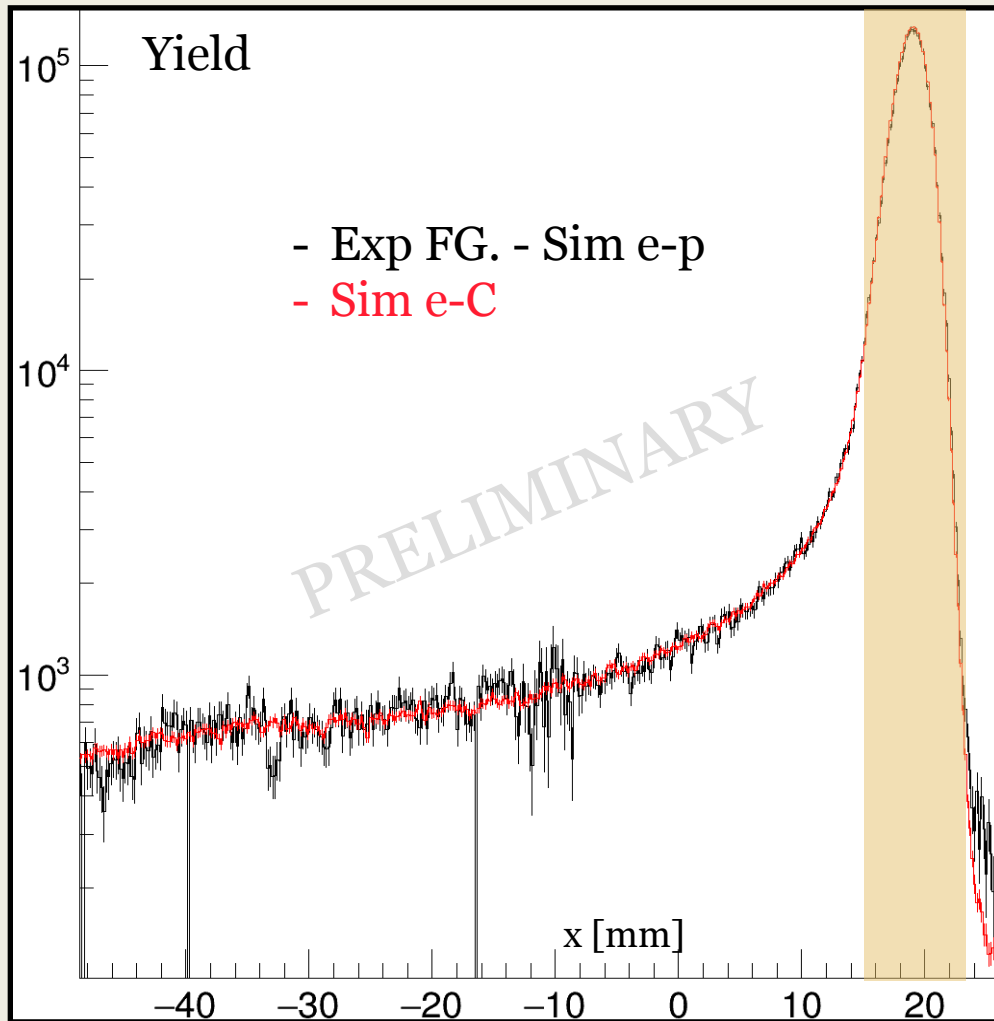


# Simulation



# Simulation

Integration regions

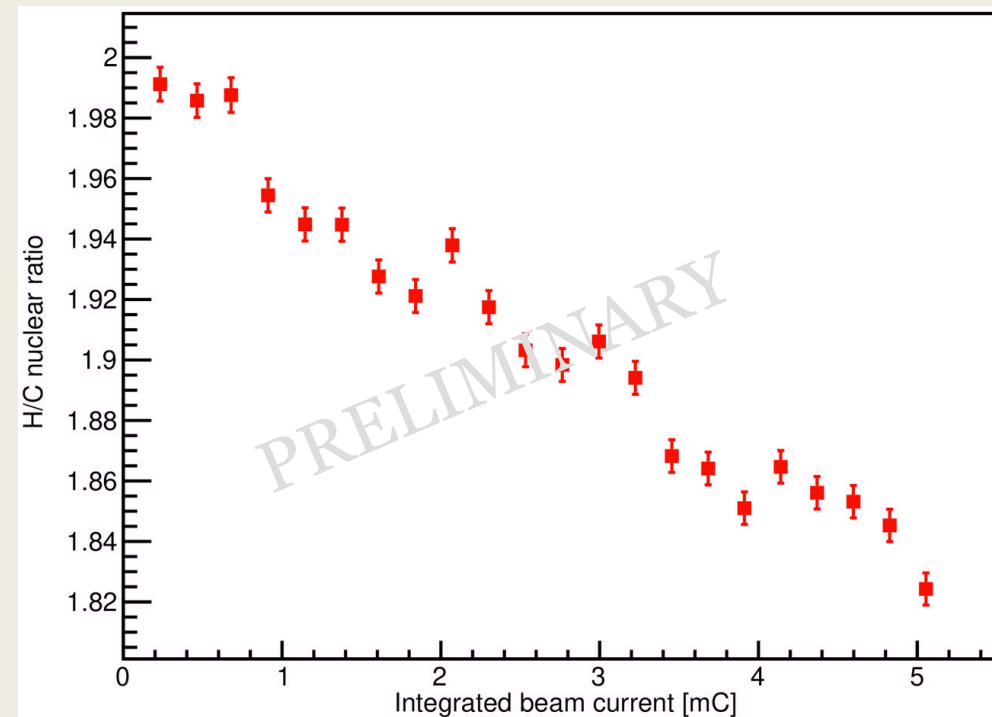
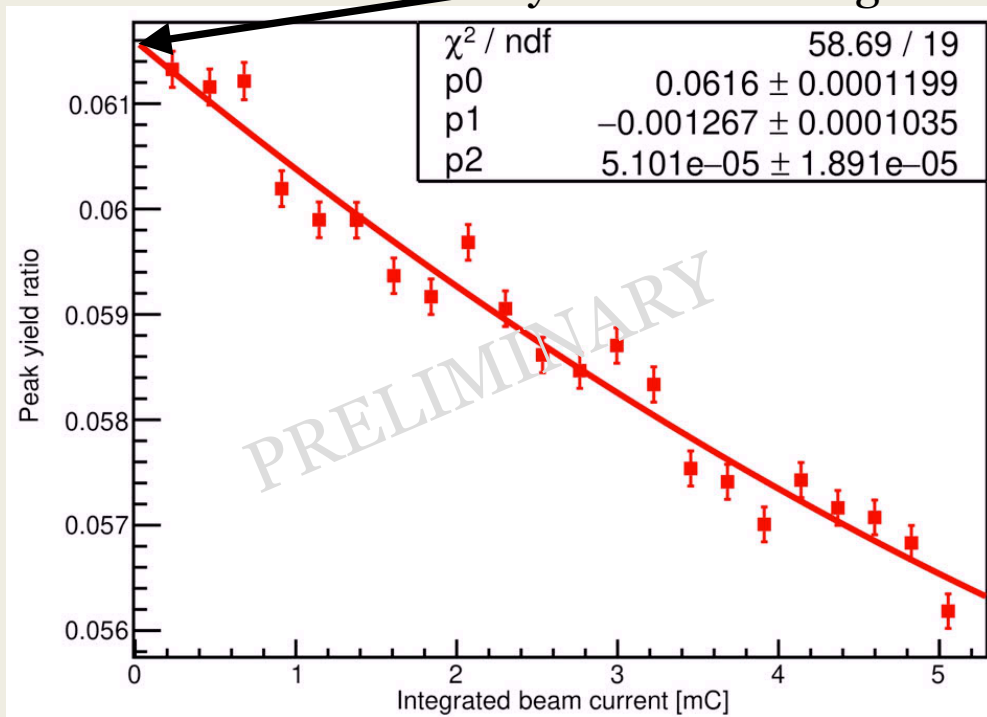


# Analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-p} = \frac{N_{e-p}/N_{e-C}}{N_p/N_C} \left(\frac{d\sigma}{d\Omega}\right)_{e-C}$$

H/C evolution study with SP2:

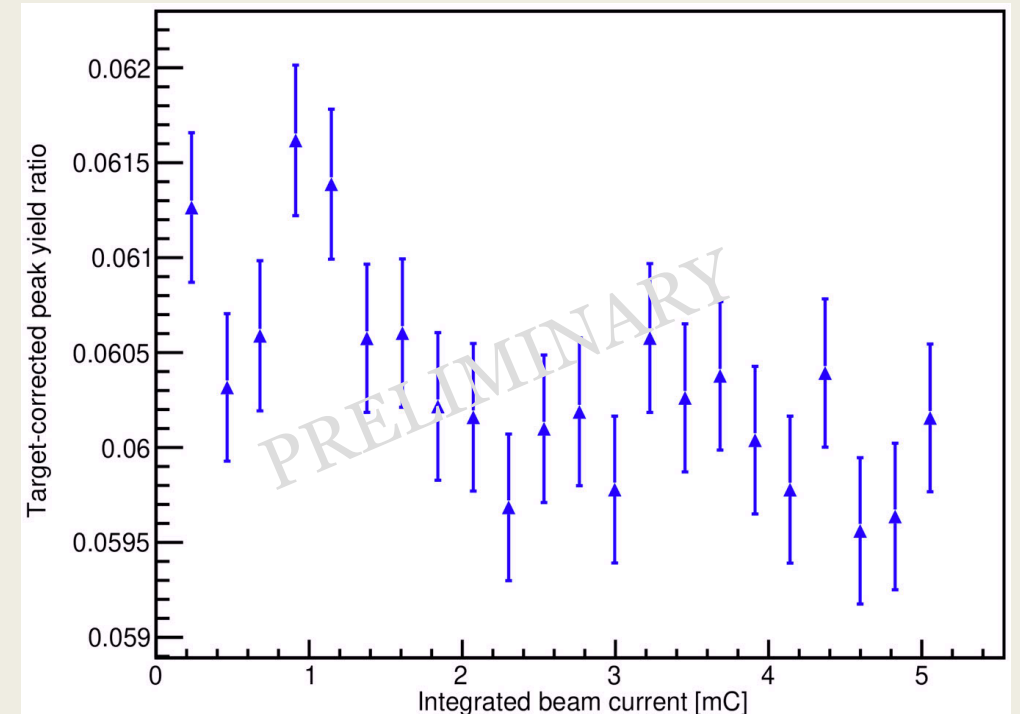
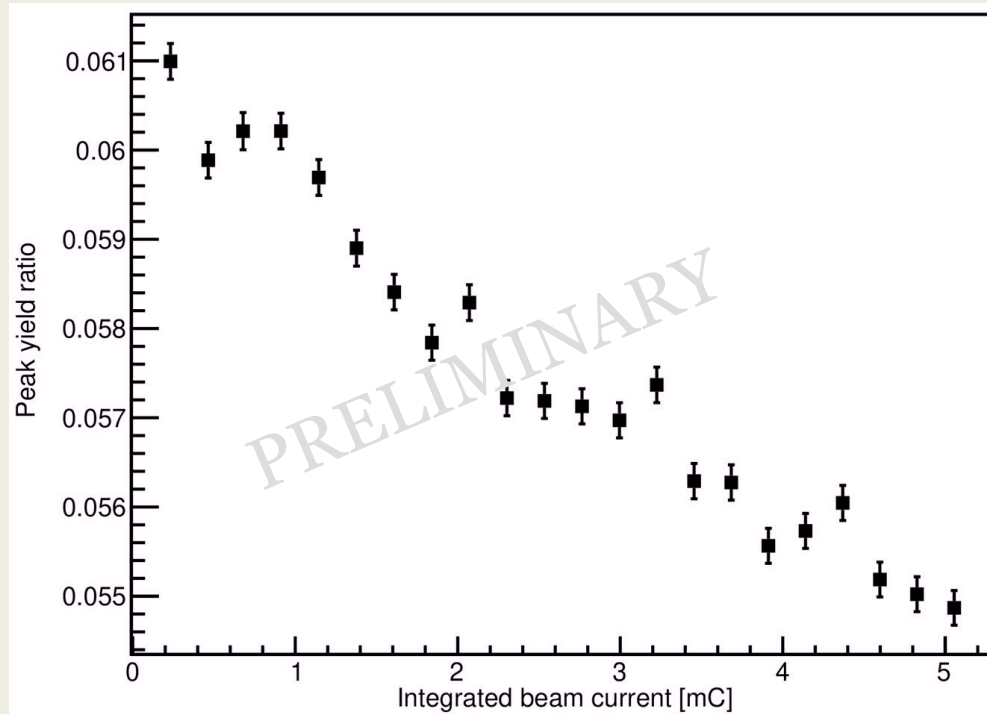
Polynomial 2 fitting



# Analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-p} = \frac{N_{e-p}/N_{e-C}}{N_p/N_C} \left(\frac{d\sigma}{d\Omega}\right)_{e-C}$$

Correction of the H/C evolution on SP1:



# Coulomb distortion

- Different corrections for e-p & e-C

$$\bullet \left( \frac{d\sigma}{d\Omega} \right)_{e-p} = \left( \frac{d\sigma}{d\Omega} \right)_0 \frac{(1 + \delta_{Fesh})G_E^2(Q^2) + (1 + \delta_{Tamae})^{\frac{\tau}{\epsilon}}G_M^2(Q^2)}{(1 + \tau)}$$

$$\text{with } \delta_{Fesh} = \frac{\pi\alpha \sin \frac{\theta}{2}(1 - \sin \frac{\theta}{2})}{\cos^2 \frac{\theta}{2}} \text{ and } \delta_{Tamae} = \frac{\pi\alpha \sin \frac{\theta}{2}(2 + \sin \frac{\theta}{2})}{1 + \sin^2 \frac{\theta}{2}}$$

T. Tamae, Phys. Rev. C **102** (2020), 022502

$$\bullet \left( \frac{d\sigma}{d\Omega} \right)_{e-C} = \left( \frac{d\sigma}{d\Omega} \right)_0 (1 + Z\delta) F_C^2(Q^2)$$

Calculated by DREPHA

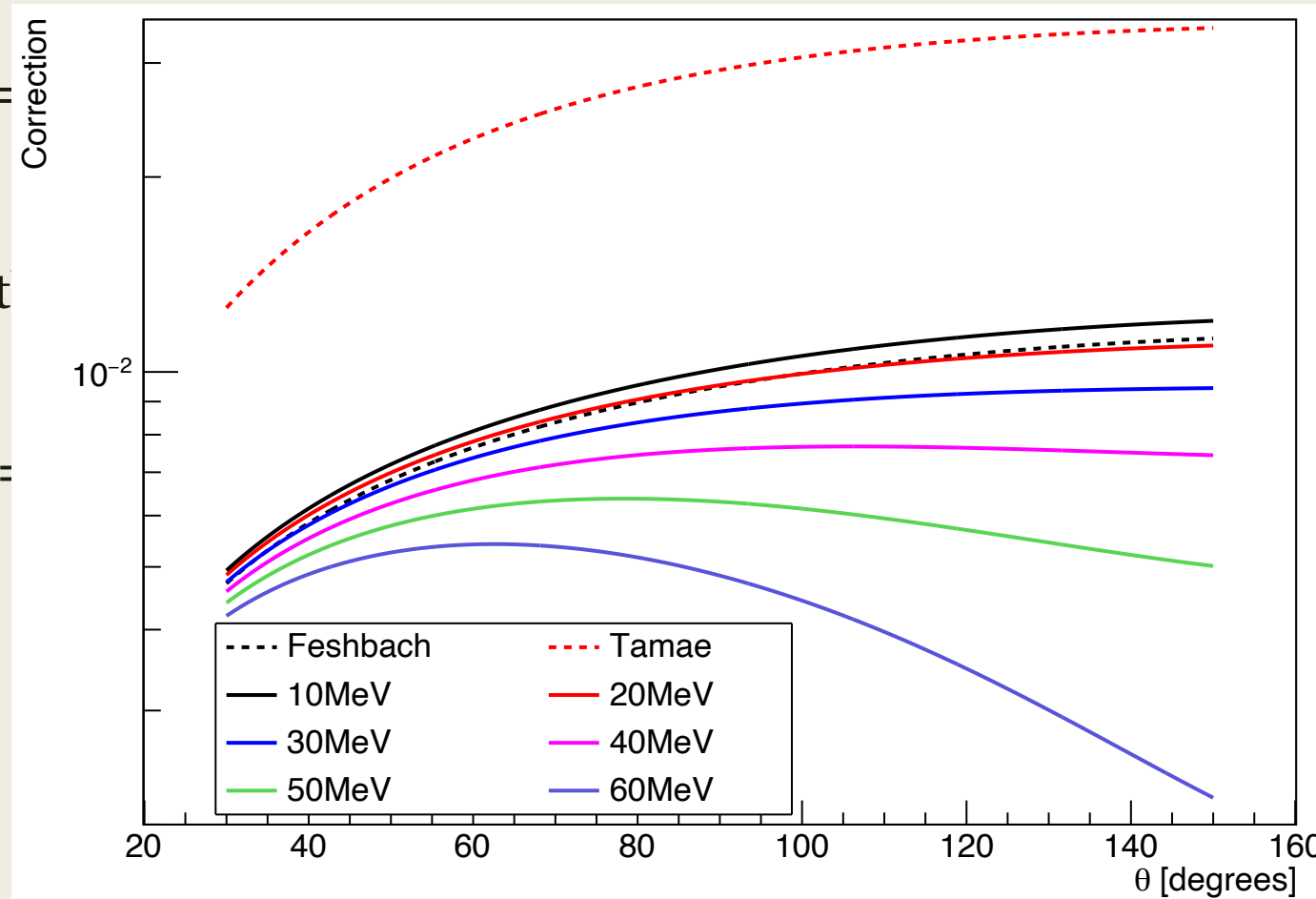
# Coulomb distortion

- Different corrections for e-H & e-C

- $\left(\frac{d\sigma}{d\Omega}\right)_{e-p}$

with

- $\left(\frac{d\sigma}{d\Omega}\right)_{e-C}$



$\ln \frac{\theta}{2}$

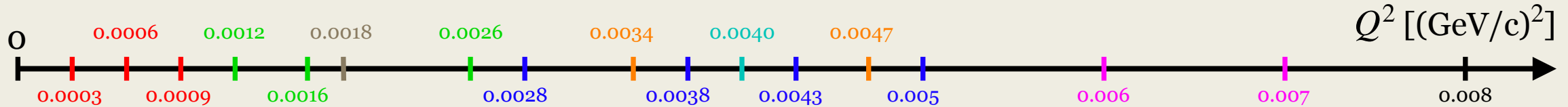
022502

# Conclusion

- Cross-section measurement:

- ➔ 17 points with  $3 \times 10^{-4} \leq Q^2 \leq 8 \times 10^{-3} \text{ (GeV/c)}^2$
- ➔ Completed throughout 2023 & 2024 (~9 weeks)

2023/05: 50 MeV  
2023/09: 42 MeV  
2023/10: 50 MeV  
2023/10: 21 MeV  
2024/01: 50 MeV  
2024/03: 50 MeV  
2024/04: 60 MeV  
2024/10: 60 MeV



- Data analysis almost complete!

➔ Results coming very soon!

# Thanks to all ULQ<sup>2</sup> collaborators

D. Abe<sup>1</sup>, R. Danjo<sup>1</sup>, O. Fujishima<sup>2</sup>, T. Goke<sup>1</sup>, Y. Honda<sup>1</sup>, Y. Ishikura<sup>1</sup>, K. Ishizaki<sup>1</sup>, K. Haak<sup>3</sup>,  
K. Hotta<sup>1</sup>, R. Kagami<sup>4</sup>, H. Kikunaga<sup>1</sup>, H. Kobayashi<sup>4</sup>, M. Kohl<sup>5</sup>, C. Legris<sup>1</sup>, Y. Maeda<sup>2</sup>,  
Y. Maeda<sup>4</sup>, D. Marchand<sup>6</sup>, S. Miura<sup>1</sup>, M. Miyabe<sup>1</sup>, E. Morris<sup>7</sup>, M. Mitsui<sup>2</sup>, T. Muto<sup>1</sup>,  
I. Nagasawa<sup>1</sup>, Y. Nagano<sup>8</sup>, K. Nanbu<sup>1</sup>, R. Obara<sup>1</sup>, T. Ohnishi<sup>9</sup>, S. Sasaki<sup>1</sup>, K. Shibata<sup>1</sup>, T. Suda<sup>1</sup>,  
M. Tachibana<sup>4</sup>, K. Takahashi<sup>1</sup>, D. Taki<sup>1</sup>, T. Tamae<sup>1</sup>, O. Tokiyasu<sup>1</sup>, K. Tsukada<sup>4</sup>, E. Voutier<sup>6</sup>,  
T. Yamauchi<sup>1</sup> and K. Yoshimoto<sup>1</sup>

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<sup>2</sup>Miyazaki Univ., Dept. of Applied Phys.

<sup>3</sup>MSU, FRIB

<sup>4</sup>Kyoto Univ., ICR

<sup>5</sup>Hampton Univ., Phys. Dept.

<sup>6</sup>CNRS/IN2P3, IJCLab

<sup>7</sup>Univ. of East Anglia

<sup>8</sup>Yamagata Univ.

<sup>9</sup>RIKEN Nishina Center

**THANK YOU FOR YOUR ATTENTION**